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Design and construction solar steam sterilizer

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Abstract

Doctors, especially surgeons in remote areas, need help to overcome the problem of transmission of infection resulting from the repeated use of surgical instruments without sterilization, and that is why researchers sought to find solutions. This study presented a design and model made for a low-cost solar sterilizer. It relied on benefits from the glasshouse properties to generate the wet steam that was required for sterilization at a temperature of $121.1°C$ and a pressure of 2.1 bar inside an aluminum pressure cylinder that was placed inside an insulated chamber, whose dimensions were 50 cm wide, 30 cm high, and 93 cm deep. Its front face was made of 10 mm-thick thermal glass. The top face was used as a frame for fixing the cylinder. The outer surface of the cylinder was coated with a matte black paint to increase heat absorption. The model was tested in the absence of surgical equipment using half a liter of pure water, and it took 128 minutes to achieve a steam with the properties necessary for sterilization. The test started when the temperature of the water inside the cylinder was 56.1°C. In climatic conditions in which the average intensity of solar radiation was 903 W/m^2 and the average ambient temperature was 34°C. Then the performance was tested with the presence of 1.2 kg of instruments. The presence of the surgical instruments increased the time required to achieve the temperature and pressure required for sterilization by 25.78%. And to increase the thermal enablement of the system, reflective panels were placed to reflect the solar radiation towards the surface of the cylinder. This procedure achieved a 6.2% reduction in the time required for the sterilization requirement for steam. The tests were conducted over several days and under different conditions, each achieving the necessary steam for sterilization.

Keywords: Solar energy, Solar autoclave, Solar steam sterilization.

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Nomenclature

A: The total area of the glass layer through which solar radiation penetrates into the chamber (m^2).

A_{ref}= The surface area of reflecting plates (m^2).

C_p: Specific heat $J/kg.k$

$C_{(p,AL)}$: The Specific heat for aluminum [3]=0.896 KJ/kg. k.

$C_{(p,s.i)}$: Specific heat of surgical instruments that made of stainless steel[3]=468 J/ Kg. K.

D : Inside diameter of sterilization cylinder (m).

E: Rate of energy (W).

h_w: Heat transfer coefficient ($W/m^2.k$).

h: Enthalpy (kJ/kg).

I_{tatal}: The average intensity of solar radiation falling on the surface of the glass (W/m^2).

K: Thermal conductivity ($W/m.k$).

K_{st}: Thermal conductivity of steel [3]= 16.3 $W/m.K$.

$K_{(g,w)}$: Thermal conductivity of glass wool [3]=0.038 $W/m.K$.

K_{alu}: Thermal conductivity of alucobond for 6mm thickness [5]=0.35 W/m. K.

L: Height of sterilization cylinder (m).

m_{water}: Amount of water inside sterilization cylinder(kg).

$m_{(p,s.i)}$: Surgical instruments mass (kg).

Q_{losses}: The heat loss through the chamber's walls to the ambient(W).

Q_{abs}: Amount of energy absorbed by the cylinder body (J).

Q_{water}: Amount of energy absorbed by the water (J).

$Q_{reflected}$: Amount of energy reflected by the reflecting plates(J)

r_{steel}:Steel sheet reflectivity(-)[3]=0.9

R_b: The geometric factor (-).

T_{amb}: Ambient temperature.

T_1: Initial temperature inside sterilization cylinder.

T_2: Final temperature inside sterilization cylinder.

U_L : Overall Heat transfer coefficient ($W/m^2.k$).

V_W: Wind speed (m/s).

$\forall$: Volume (m^3)

v: Specific volume (m^3/kg).

$X_{st} = t_1$: Thickness of steel layer.

$X_{g.w}$:Thickness of glass wool.

$X_{alu} = t_3$:Thickness of alucobond.

β: Tilt angle (Degree)

ρ : Density kg/m^3

ρ_{AL}: The density of aluminum, [3] =2700 kg/m^3

ρ_{st}: The density of steel [3]=7865 Kg/m^3

τ : Transmissivity

τ_g: Glass transmittance (0.92)[7].

Δt : The period time that required to achieve T2 from T1 (S)

φ: Latitude angle (Degree)

ω: Hour angle (Degree)

σ: Declination angle (Degree)

θ_z: Zenith angle (Degree).

1. Introduction

One of the most significant topics that researchers concentrated on in their studies was human life. Taking care of one's health is the first step toward preserving one's life. As a result, studying to advance in the field of health became one of the most important interests and accomplishments of researchers. And the problem of transmission of diseases through the repeated use of non-sterile surgical instruments, was a problem that stopped researchers, that caused the spread of epidemics and many lives were lost. The researchers labored tirelessly to identify normal sterilizing standards and procedures, as well as develop and manufacture sterilization equipment. After conducting several tests and analyses, they discovered a variety of sterilization procedures, the most important and simple of which was steam sterilization. This sterilization necessitates the use of steam at 121.1°C and a pressure of 2.1bar [10]. The sterilizers devices that were produced, called the autoclave, succeeded in completing the sterilization process based on the results of the tests. With the use of autoclaving, a new problem has emerged, which was the impossibility of using this device in remote areas where electricity is not available, and therefore, many areas were deprived of servicing this device. This was a challenge for scientists and researchers. The need prompted researchers to find alternatives to use altrnative energies, and in particular, solar energy, because it is the most available among those energies, and the most appropriate. Researchers focused on using the sun's energy for their designs for solar sterilizers. It is worth noting that these research and studies produced designs and models for solar steam sterilizers.
It seems that the reason for focusing on this type of sterilization was that they do not require high heat, as well as because they are easy to produce using solar concentrators that focus solar energy on water and thus generate the steam needed for sterilization. As well as using some nanomaterials that help to invest the largest amount of solar energy to generate steam. Among those studies that served the field of solar sterilization.

Sarah S. Trabia's study [8] presented a design consisting of 12 copper tubes placed diagonally on a stand. It is connected to a main tube located in the head of the holder, which in turn is connected to an aluminum pressure cylinder containing the instruments to be sterilized, with a capacity of 25 liters. All parts of the model are thermally insulated. The design achieved steam inside the sterilizing chamber of 121° C and 1.172 bar.

N.K. Sharma et al. [6] them study came up with a design that succeeded in achieving the standards required for the sterilization of surgical instruments. The design consists of a parabolic trough-shaped reflective surface that reflects solar radiation toward a metal tube passing through a transparent pressure tube. Water passes inside the metal tube to take heat through the walls of the tube to generate steam, which in turn rushes towards the pressure chamber containing the materials to be sterilized. The copper metal tube has a diameter of 58 mm and a length of 1800 mm, while the area of the inverted basin is (1* 1.6) m^2. The steam inside the container achieved a maximum temperature of 132°. and a pressure of 15 psi.

Asfafaw et al. [1] This study developed a solar sterilizer with a design that consists of a parabolic surface solar condenser of 1.75 m in diameter covered with reflective aluminum foil, a pressure cylinder 3 mm thick, and a system support structure, in addition to a solar tracking system. Surgical instruments are placed inside the cylinder, which has sides insulated with a 25 mm thick insulator to reduce heat loss. The results were successful and effective as the numerical and experimental results were validated using conventional sterilization procedures. Temperatures reached around 145°C and were maintained for more than 20 minutes during practical testing for the model produced, which met sterilization standards.

Lin et al. [11] presented a recent study in India, which included a factory design and model that included a solar collector with an area of 2 m^2. The design is mainly made of black heat-absorbing material, which is a copper plate with a black coating that has been produced and developed in recent years. It absorbs heat to transfer it directly to a group of tubes located below it, where water passes inside the tubes to absorb the heat absorbed by the copper plate, and thus steam is generated to rush into the pressure chamber where medical materials inside. With aluminum mirrors on the sides that reflect the solar radiation towards the copper plate, the model achieved steam generation at a temperature of 125 °C This temperature was maintained for 30 minutes, which was enough for the sterilization process to be successful.

2. The design idea

In this study, the researchers invested the glasshouse properties to collect solar energy and convert it into thermal energy to generate steam needed for sterilization to be able to sterilize surgical instruments.

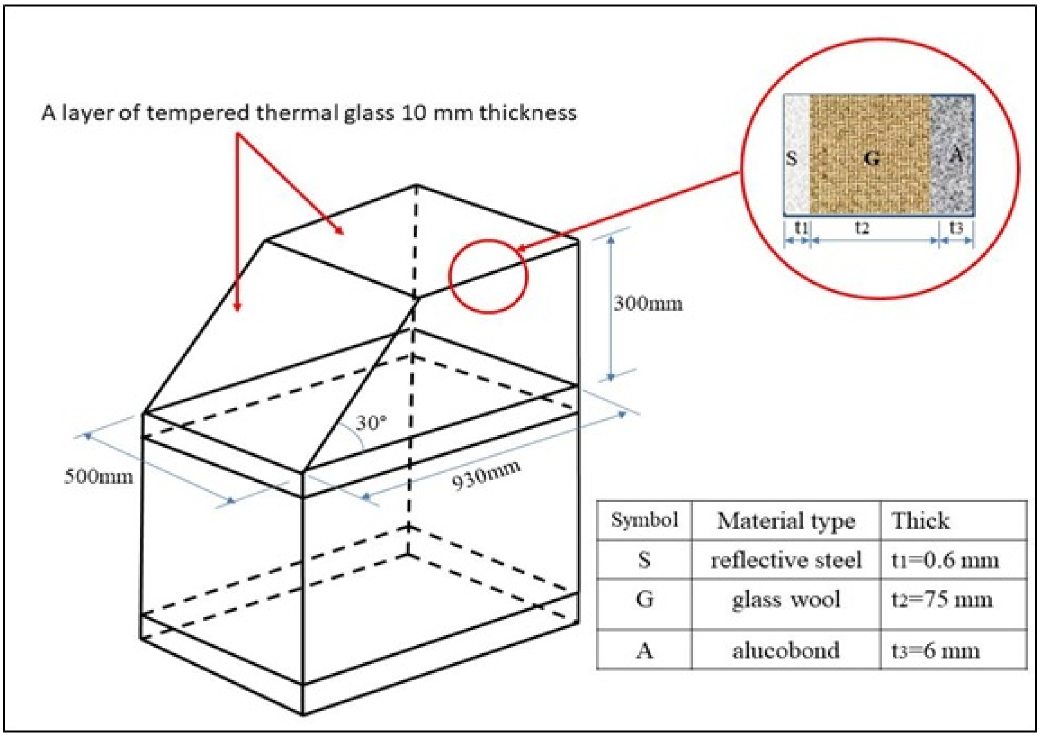
2.1. Experimental settings

The design involved the building of a steam sterilization chamber, which was a chamber with a total volume $0.1395m^3$, whose dimensions were 50 cm in width and 30 cm in height. While the length was 93 cm, the walls of the lower, side, and rear chamber are made up of

three layers: an inner layer of reflective steel with a thickness of 0.6 mm, a layer of glass wool a thickness of 75 mm, and an Alucobond 6 mm thick outer layer. The chamber's rear wall was a gateway constructed of the same layers as the chamber's other walls. While the front face was a layer of tempered thermal glass with a thickness of 10 mm, inclined at an angle of 30° as shown in Figure 1, the upper face of the chamber was in the form of a frame on which an aluminum cylinder was installed, with an internal diameter of 290 mm and a height of 230 mm and 5 mm thick. Its cover was provided with manual locks to tighten the fastening on the body of the cylinder. To control the value of the steam pressure inside the cylinder, the cover has a pressure gauge and a relief valve. It was set at 2.1 bar with a manual opening and closing valve to remove air before starting the sterilization process and to remove steam after the sterilization process was complete. This cylinder was originally a table autoclave. In order to avoid heat loss from the cylinder cover, a cube cover was manufactured with its front face being a layer of tempered thermal glass inclined at an angle of 30°, the inner walls of which were covered with reflective foil. The outer surface of the cylinder and its cover were painted with matt black paint to absorb maximum amount of solar radiation heat, as shown in Figure 2. Surgical instruments to be sterilized are placed inside the cylinder. The system is equipped with a solar tracking system that allows the system to track the sun from east to west.

2.2. Final design of the device

After addressing the design and manufacturing problems, the device took form as a solar collector with a length of 66 cm, a depth of 1 m, a height of 134 cm from the rear, and a front height of 66 cm. All of these dimensions were measured from the outside, taking into consideration the thickness of the walls. In addition to these heights, there is the height of the wheels that support the base, which was 20 cm, and readily revolve along their vertical and horizontal axes. In order to increase the thermal enablement, the researchers decided to add sheets of reflective steel arranged in a cone



Symbol	Material type	Thick
S	reflective steel	t_1=0.6 mm
G	glass wool	t_2=75 mm
A	alucobond	t_3=6 mm

Figure 1: Schematic diagram of sterilization chamber details.

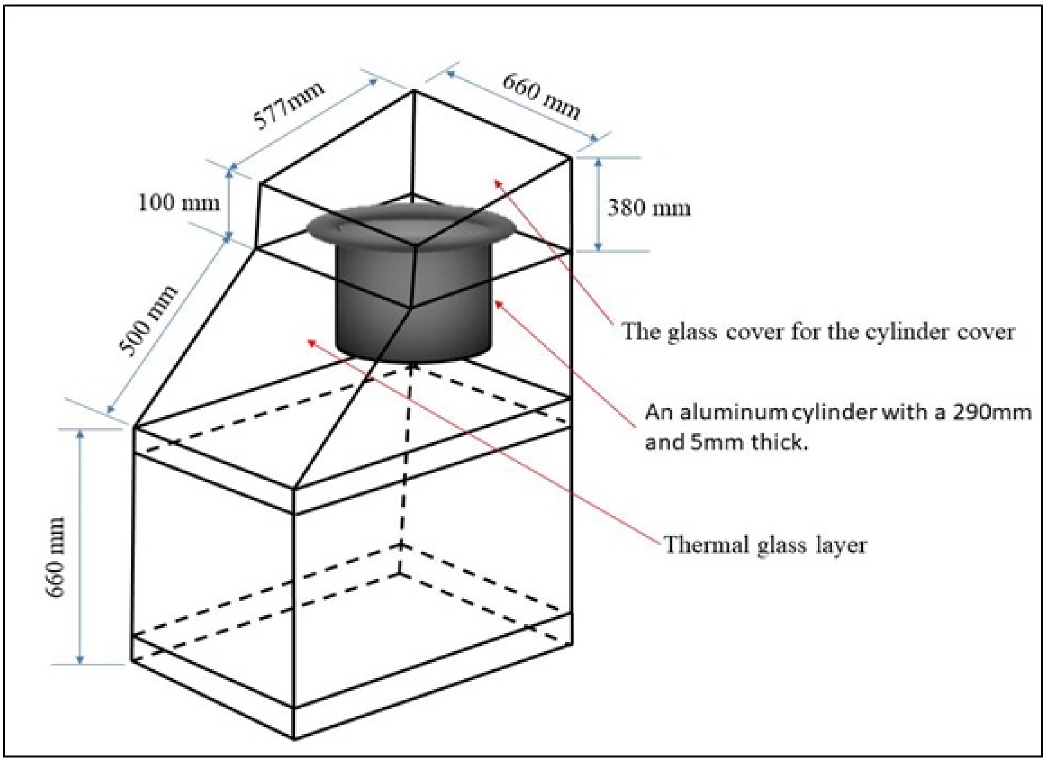


Figure 2: A simplified diagram of the steam sterilizer chamber.

shape around the steam sterilization cylinder, in order for these panels to increase the reflection of solar radiation towards the cylinder. The device rotates around its axis of rotation during the solar tracking process, which was placed in the center of the base, where rotates around a fixed point of rotation, which is a rectangular base that was manually lowered by a screw to rest on the ground, as shown in Figure 3.

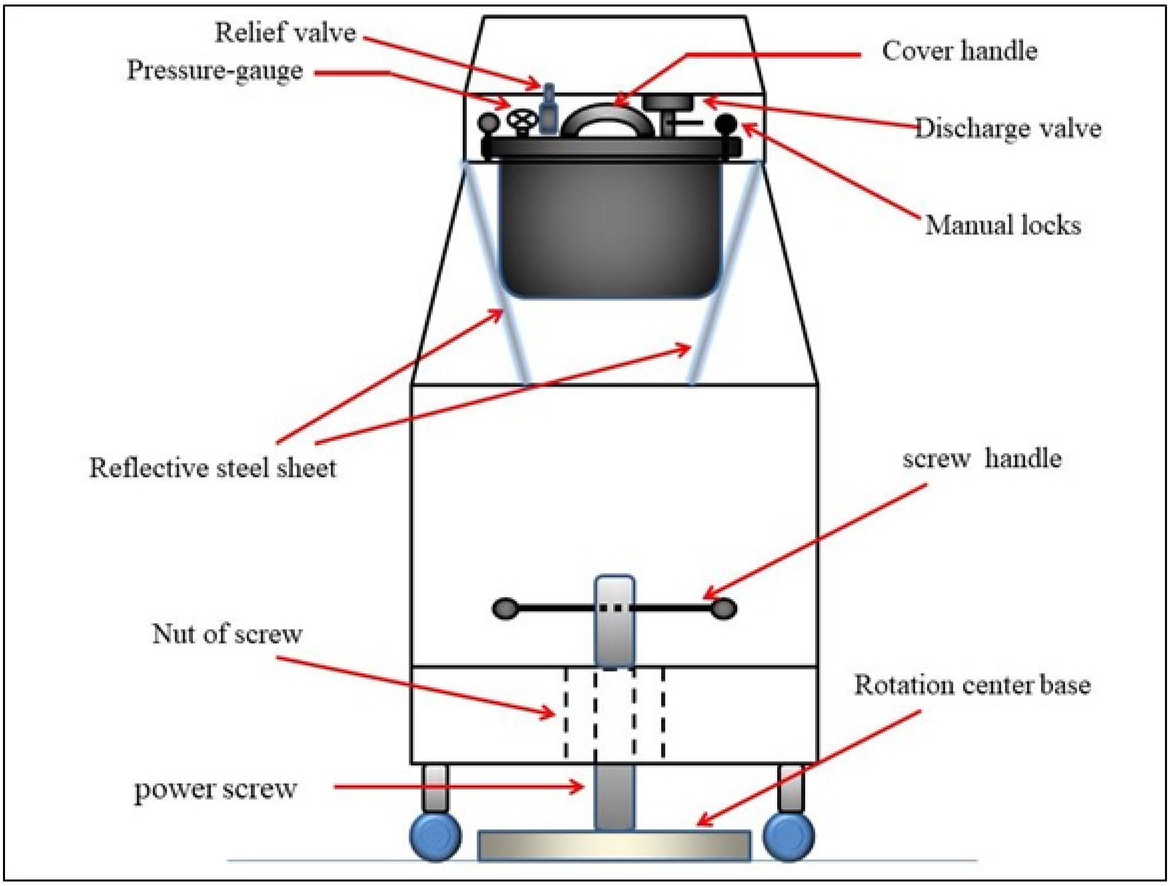


Figure 3: A simplified diagram showing front view of the final shape of the device.

A simplified diagram showing front view of the final shape of the device

3. The governing equations

Relying on the heat balancing, the governing equations of the system were determined, thus knowing the amount of heat absorbed by the water in the steam sterilization chamber and the time required to obtain steam with the properties necessary for sterilization, as follows:

$$\dot{E}_{\text{in}} - \dot{E}_o = \dot{E}_{\text{system}} \tag{3.1}$$

The heat entering the chamber is the heat that passes through the glass layer, and it certainly depends on the intensity of the incident solar radiation $(\mathbf{I}_{\text{total}})$, surface area(A), and transmittance $(\tau_{\mathbf{g}})$of the glass layer. Because the glass face is tilted at an angle, the geometric factor $(\mathbf{R_b})$ must be considered to convert the intensity of the radiation falling vertically on the horizontal surface to perpendicular to the surface of the inclined glass. Thus, when all these terms are multiplied, they equal the input heat $(\dot{\mathbf{E}}_{\text{in}})$. This heat is distributed to heat the metal of the cylinder through the energy absorbed by it $(\mathbf{Q}_{\text{abs}})$ during the time, and also to evaporate the water, which is the energy absorbed by the water $(\mathbf{Q}_{\text{water}})$ during the time. The sum of these two heats gives the heat absorbed by the system $(\dot{\mathbf{E}}_{\text{system}})$, as well as the heat lost to the outside through the walls $(\dot{\mathbf{E}}_{\mathbf{o}})$, and depends on the thickness and type of materials used in the wall layers as shown in Figure 4.

Accordingly, the heat entering the chamber will be equal to the sum of the heat absorbed by the system (the cylinder and the water) and the heat lost to the ambient. Thus, the mathematical relationship can be written as:

$$I_{\text{tatal}}\ \mathrm{A}\ \mathrm{R}_b\ \tau_g - \dot{Q}_{\text{losses}} = (Q_{abs,cylinder} + Q_{\text{water}})/\Delta t \tag{3.2}$$

From Figure 2, A=0.54 m^2.

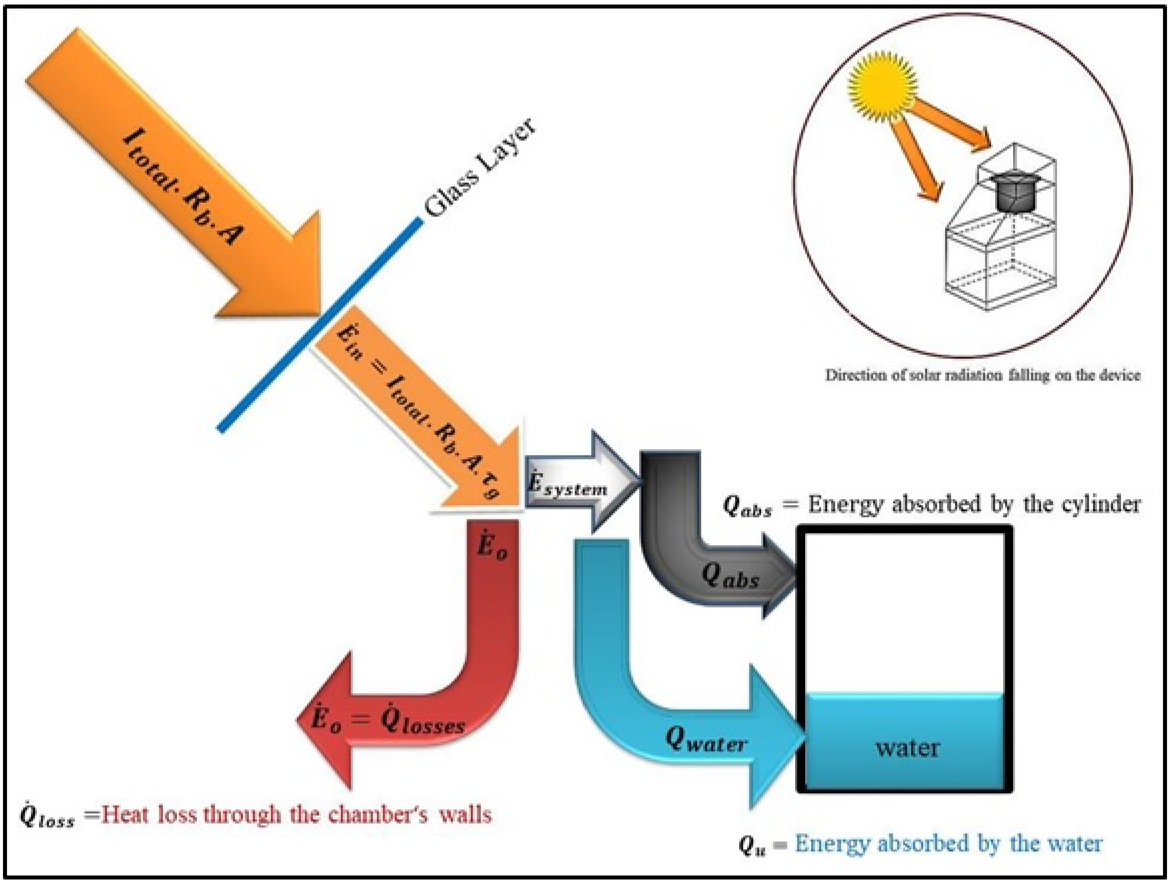


Figure 4: A simplified diagram of the Thermal Balance for the chamber.

To calculate the geometric factor R_b [7]

$$R_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\cos(\varnothing - \beta)\cos\delta\cos\omega + \sin(\varnothing - \beta)\sin\delta}{\cos\varnothing\cos\delta\ \cos\omega + \ \sin\varnothing\ \sin\delta} \tag{3.3}$$

To calculate the heat absorbed by cylinder $Q_{abs,AL}$ [3]:

$$Q_{abs,\ \ AL} = \rho_{\text{AL}} \ \forall \ C_{p,AL}(T_2 - T_1) \tag{3.4}$$

As for the volume of the steam strilization cylinder (aluminum cylinder), it can be calculated according to its dimensions, which are shown in Figure 5.

$$\forall = \pi D\ L\ t + 2\{\ \frac{\pi}{4}(D + 2t)^2\ t\} \tag{3.5}$$

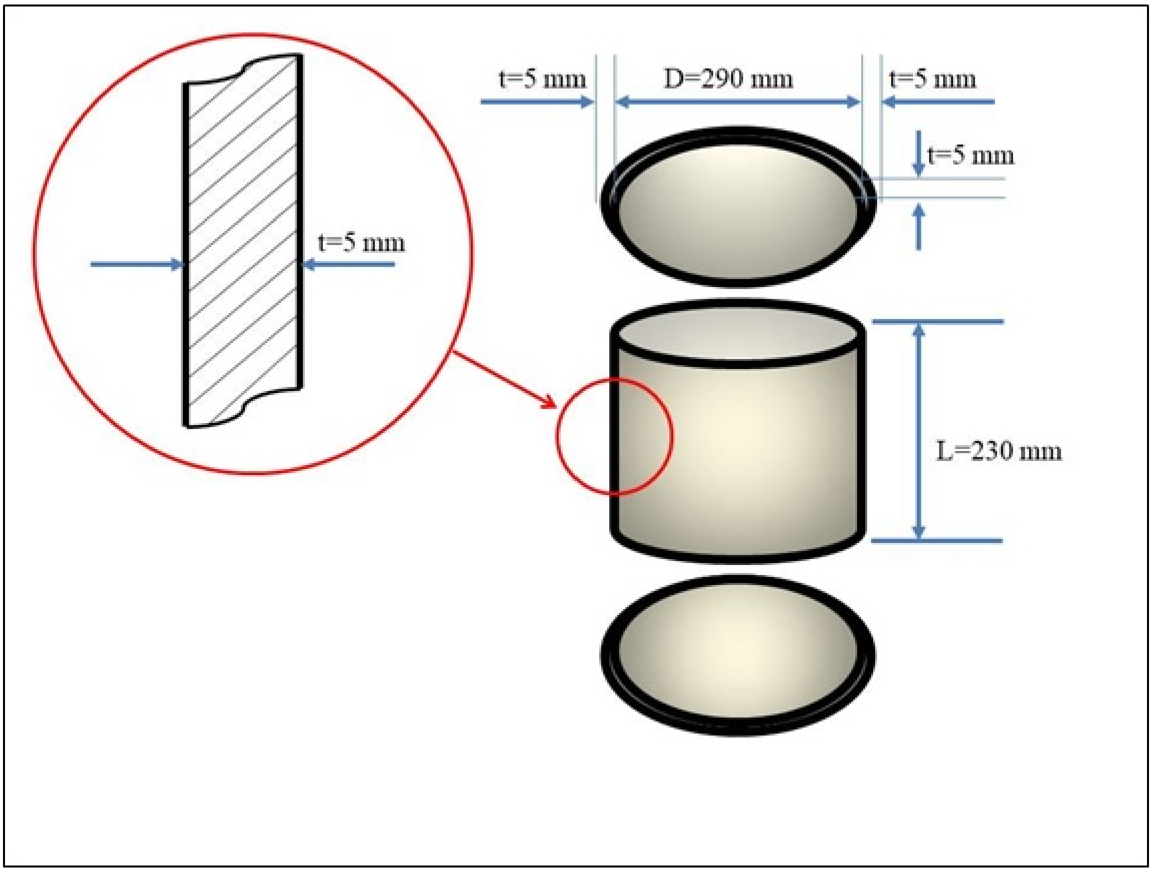


Figure 5: The dimensions of the steam sterilizer cylinder.

To calculate the amount of heat losses to the external environment through the walls of the sterilization chamber Q_{losses}[3]

$$Q_{\text{losses}} = U_L \; A_{\text{surface}} \; (T_2 - T_{\text{amb}}) \tag{3.6}$$

$$U_L = \frac{1}{\sum R} \tag{3.7}$$

$$\sum R = R_{\text{conduction}} + R_{convection,out} \tag{3.8}$$

$$R_{\text{conduction}} = \frac{X_{\text{st}}}{K_{\text{st}}} + \frac{X_{\text{g.w}}}{K_{\text{g.w}}} + \frac{X_{\text{alu}}}{K_{\text{alu}}} \tag{3.9}$$

$$R_{convection, \quad out} = \frac{1}{h_{\text{out}}} \tag{3.10}$$

Calculation of the convective heat transfer coefficient at the outer surface of the heat sterilization chamber wall [2]:

$$h_{\text{out}} = h_w = 5.7 + 3.8 \; V_w \tag{3.11}$$

By using the standard values in its equations with the dimensions of the cylinder and the walls of the sterilization chamber, the result was that the value of the heat loss lost to the external environment was $2.334\,(T_2 - T_{\text{amb}})$ Watts , as well as the value of the energy absorbed by the steam strilization cylinder (Aluminum cylinder) was 4233.6 $(T_2 - T_1)$Joules.

When surgical instruments are placed inside the steam sterilization cylinder with a mass of m kg, these instruments will absorb part of the amount of heat entering the steam sterilization chamber, and thus the term $Q_{\mathrm{abs},s.i,}$ is added to the right side of equation (3.2).

$$Q_{abs,\quad s.i} = m\ C_{p,s.i}(T_2 - T_1) \tag{3.12}$$

The amount of heat that water needs to convert from its initial temperature to steam, at the temperature required for sterilization (121.1 °C with a pressure of 2.1 bar) [9]:

$$Q_{\mathrm{water}} = m_{\mathrm{water}}(h_2 - h_1) \tag{3.13}$$

$$h_1 = C_w T_1 \tag{3.14}$$

$$h_2 = h_f + x h_{\mathrm{fg}} \tag{3.15}$$

To calculate the dryness percentage (x), the following equation is used [9]:

$$\frac{\forall}{m_w} = \ \mathrm{v}_{f1}\ + x(v_g - v_{f2}) \tag{3.16}$$

By using equation (3.16), it was found that the dryness fraction was very low 0.035, although the final temperature is $121.1°C$ when used 0.5Kg of water. This means that in the liquid phase, most of the heat that was absorbed.

Therefore, the total energy that absorbed by 0.5 kg of water to transform from a liquid at a temperature of 30°C to wet steam at a temperature of 121.1 was 228.2KJ.

When taking into account the amount of energy reflected by the reflecting plates inside the sterilization chambers, the term $Q_{\mathrm{reflected}}$ can be added to left side of equation (3.2) where:

$$Q_{\mathrm{reflected}} = (I_{\mathrm{tatal}}\ A_{\mathrm{ref}} R_b \tau_g) r_{\mathrm{steel}} \tag{3.17}$$

4. Results and discussion

The model was tested for days during a variety of environments. The testing began in the second part of Apri and continued until last of May, measuring the change in temperature and pressure of water and then steam within the steam strilization cylinder.

After the system was absorbed the initial heat during the hours preceded the test time since sunrise, The test started at 10:00 am. so that the temperature of the water inside the steam sterilizer cylinder was $56.1°C$. The increase in temperature was monitored every 20 minutes until the temperature of the water and steam inside the cylinder reached 121.1°C, at 12 and 8 minutes noon, that is, after 128 minutes, The temperature was maintained at this value for more than an hour, as shown in the Figure 6.

Also, the pressure inside the cylinder changed from 0.1 bar to 2.1 bar in 128 minutes, and it was fixed at this value by the relief valve, which means that the constant pressure caused the temperature to remain constant and this corresponds to properties of the wet steam. The weather conditions during the testing period were (10.00am - 12:08pm) with an average solar radiation intensity of 903 W/m^2 and an average ambient temperature $34.5°C$.

The previous test was repeated, but with surgical instruments weighing 1.2 kg inside the cylinder and the change in temperature and pressure inside the cylinder was recorded every 20 minutes. Although this test was conducted in weather conditions (967 W/m^2 and an average ambient temperature of 36.2 degrees Celsius) higher than in the first test, achieving the required steam took

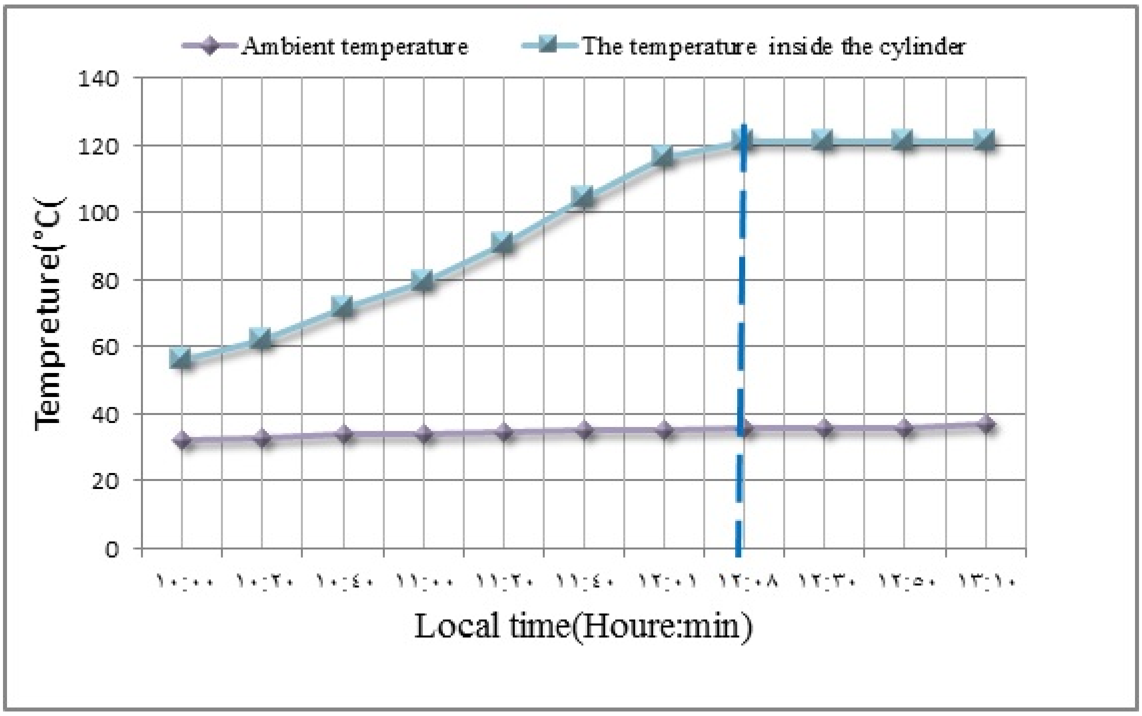


Figure 6: Steam temperature change inside the sterilization cylinder over time.

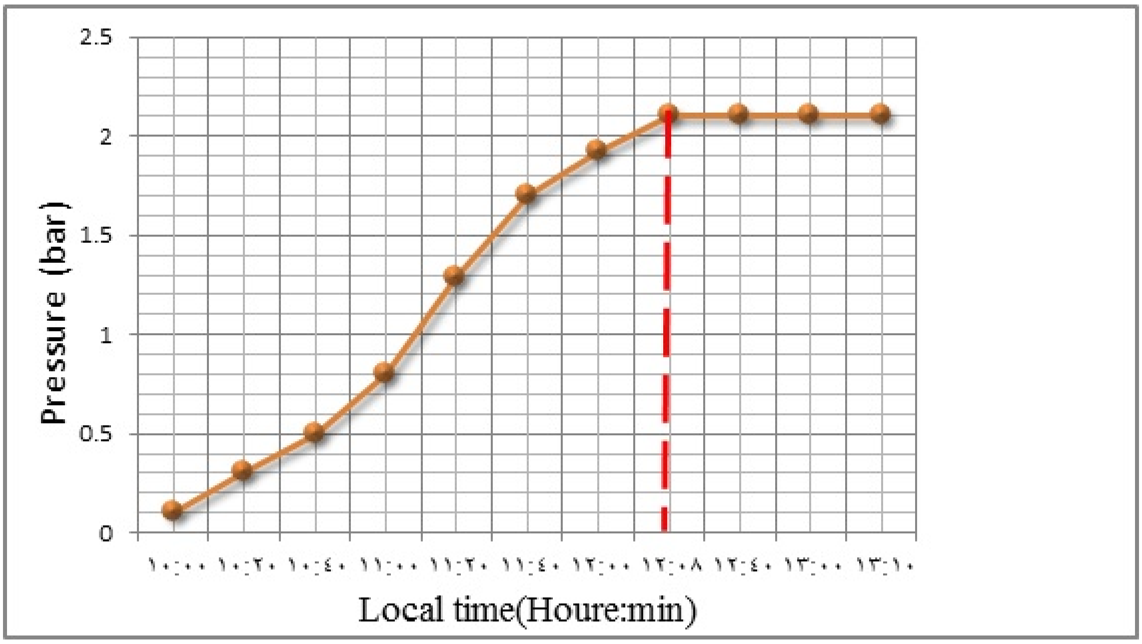


Figure 7: The pressure change inside the cylinder over time.

161 minutes Figure 8 shows the change in temperature over time and Figure 9 shows the change in pressure over time.
Based on the results obtained from the two tests above, the increase in the time to achieve sterilization requirements was 25.78%. This is because the metal medical equipment in the cylinder absorbed part of the heat energy that enters the sterilizing chamber, reducing the amount of heat absorbed by the water per unit time, which makes it take longer for the water to attain the steam at the required

properties.

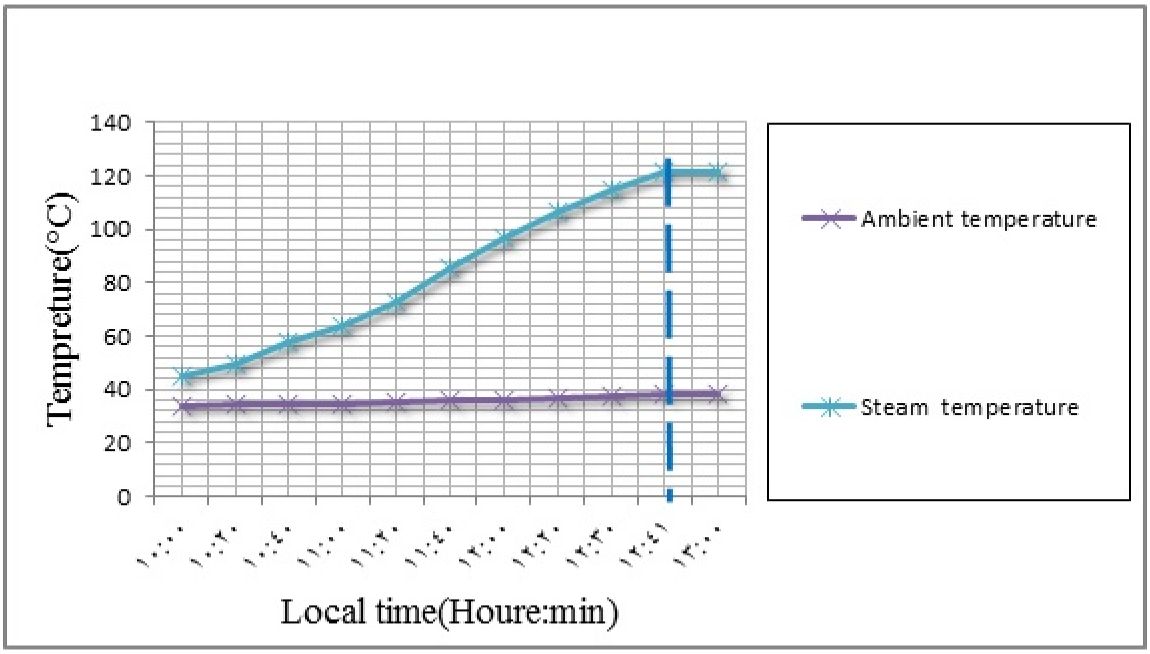


Figure 8: Steam temperature change inside cylinder over time with surgical instruments.

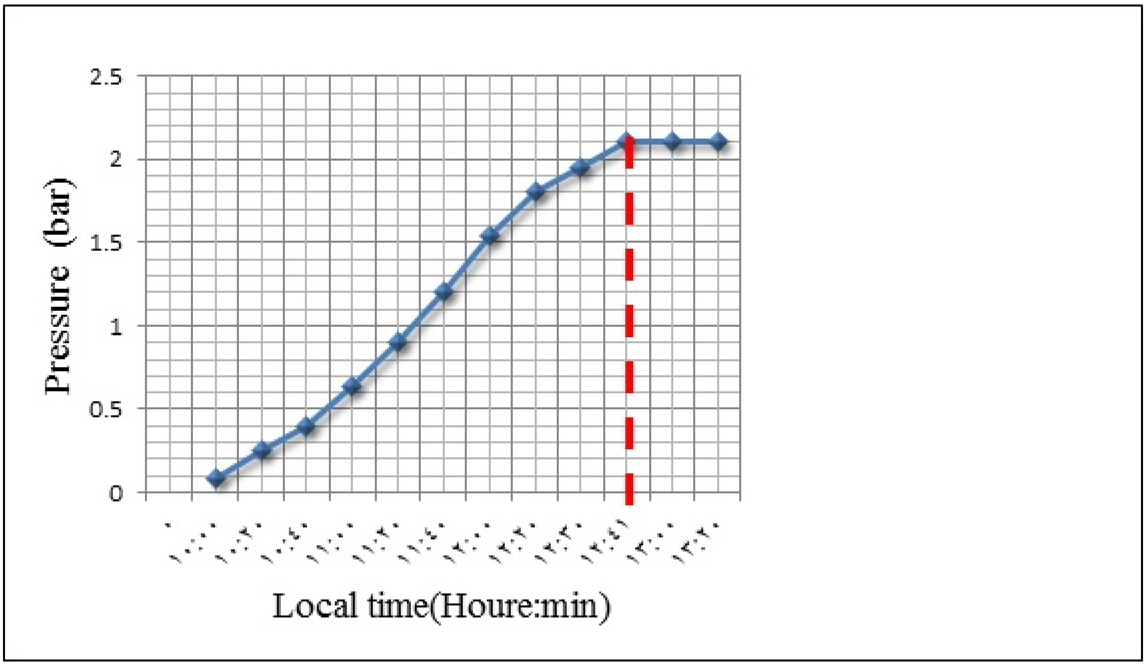


Figure 9: The pressure change inside cylinder over time with surgical instruments.

An experiment was conducted to increase the thermal enablement of the steam strilization cylinder, whereby reflective steel sheets arranged in a conical shape were added to increase the concentration of solar radiation towards the cylinder. The performance of the model was tested with 1.2 kg of surgical instruments inside the cylinder. The presence of the reflective panels increased the speed of achieving sterilization requirements compared to before they were placed, although the increase was not significiant.

Although the test was conducted in climatic conditions almost similar to those of the previous test (988 W/m^2 and an average ambient temperature of 37°C), there was an increase in the time required to achieve sterilization requirements by 6.2%, as it took 151 minutes. Figure 10 shows the temperature change and Figure 11 shows the pressure change inside the sterilization cylinder.

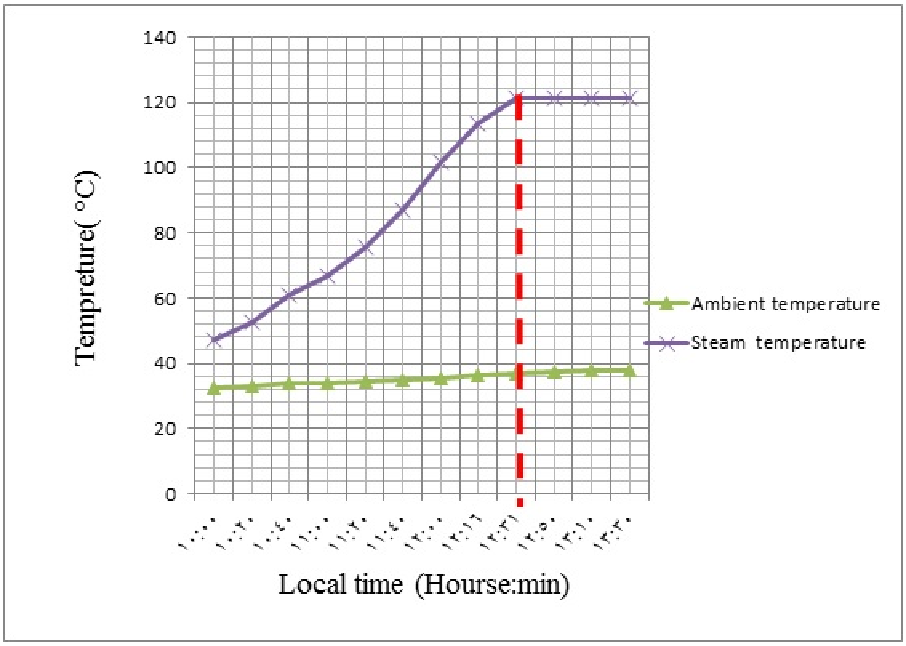


Figure 10: Steam temperature change over time with surgical instruments, and reflective cone.

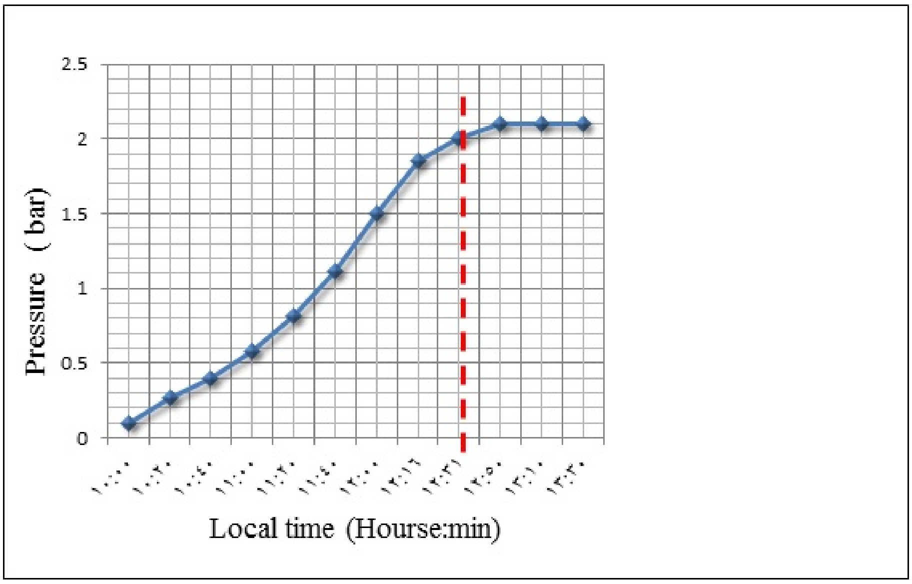


Figure 11: The pressure change inside the cylinder over time with surgical instruments, and reflective cone.

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