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Storing Solar Energy Inside Compressed Air Through A Heat Machine Mechanism

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ABSTRACT

Energy utilization in residences, industry and transportation is increasing in every other day, and knowing that most of the energy used today is supplied by finite fossil fuels is worrying enough. Since fossil resources are finite and their consumption leads to greenhouse gases to increase in the atmosphere. Global warming is a consequence of greenhouse gases accumulating in the atmosphere much more than limits. To deal with such matters governments and industries must take responsibility to develop and start using the renewable energy sources. Solar energy is the most substantial energy source in the world. One hour of the solar energy reaching the earth surface can compansate all energy need of the world for one year. In this study, it was considered that the solar energy can be stored as potential energy of compressed air. This can be simply accomplished by a heat engine. Here, air enclosed in a solar collector heats up and so does it gain pressure. Then the air pressure drives a double actuated piston cylinder mechanism. The moving piston compresses the embient air to a storage tank on the other side of the mechanism. By this way, the compressed air is always ready for use in necessary applications. Solar heat machine works according to Carnot Heat Machine Mechanism. The theromodynamic cycle is open to atmosphere; therefore, the air heated by solar energy is replaced with fresh air at the end of each cycle. The exhausted hot air can also be used for heating water or building. Here, a theoretical approach has been developed for the solar heat meachine cycle. In this approach, the thermal efficiency and solar conversion efficiency were defined with analytical relations obtained.

Keywords: *solar, energy, renewable, heat machine*

1. INTRODUCTION

Energy need and global warming are the most significant problems of this century. Fossil fuel resources are finite and as a result of fuel burning, a lot of harmful gases are released to the atmosphere, which pollutes the air and leads to the greenhouse effect. Greenhouse effect can be described as the absorption of solar radiation by the greehouse gases such as carbondioksit, methane and exhaust gases emitted to the atmosphere in course of time more than internationaly accepted limits. So their consequences cause the air in the atmophere to warm globally. A small rise in the atmophere temperature leads to major problems in climate. Global warming causes the seasonal whether changes and makes the sea level rise gradually in long term by causing the ice in the Polar Regions to melt.

Global warming threatens all living beings on the land or in the sea especially in the Polar Regions. So use of fossil fuel must be stopped and instead the renewable energy sources must take place. The conversion of renewable energy sources into electricity is inadequate at today due to inefficiencies of the conversion machines or the reasons related to costs. The other reasons for absence of the adequate renewable energy sources are the intermitent structure of them for instance sun or wind energy since they are not available at all times and another problem is directly associated with to electrical grid.

Light from the sun is our most abundant source of renewable energy; therefore, learning how to best harvest this radiation is answer to the world's future power need. One hour solar energy radiating on the earth surface is enough for annual energy consumption of the world. However, the conversion of solar energy

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[♠] Corresponding author, e-mail: *hasan.duz@batman.edu.tr* into electricity is costly and inefficient with today's solar conversion machines and methods used. Storing solar energy is also another problem of renewable energy to be tackled with nowadays. The best storage technique known today is the compression of air into a tank or a cavity such as a closed mine or natural rock under the ground or by melting the salt at solar power plant by mechanical work supplied by the solar energy. Due to the high costs of the solar energy conversion systems, here, another method is considered. In this method, the solar energy is stored as the potential energy inside a storage tank as compressed air. A heat machine can simply be able to do the solar energy conversion process. Through that heat machine, the sunlight is converted into heat through an absorber surface of a solar collector integrated with the heat machine so that the air in the enclosed space of solar collector will be heated by the absorber plate. The heated air can produce mechanical work by piston movement in a cylinder enclosure. The produced mechanical work can be utilized to compress the ambient air to a storage tank by another piston movement. By this way, the solar energy is converted to potential energy inside compressed air. After this process, compressed air in storage tank is ready for use in necessary applications such as being accompanied with a hybrid electrical compressor or being used with an air conditioning unit to cool the houses.

The solar conversion systems used today can be classified as the photovoltaic solar panels, solar power plant and solar towers. Most of the photovoltaic solar panels used today consist of thin silicon discs that convert sunlight into electricity. These discs act as energy sources for a wide variety of uses, including: calculators and other small devices; telecommunication devices; rooftop panels on individual houses; and for lighting, pumping, and medical refrigeration works in villages in developing countries. The efficiencies of such solar modules vary between 15-25% percent according to cost of the panels used ([1], [2], [3]).

A solar power plant is another solar conversion method which works on thermodynamic steam power cycle to produce electricity. Water is boiled at high temperature while it is passing through a solar tower exposed to the sunlight reflected from many mirrors deployed on the land surrounding the tower plant. The solar conversion efficiency in such plants varies between 20-30%. However, the solar power plants are cost effective due to its first investment cost according the fossil fuel consuming power plants; however, different from fuel consuming systems, it is a clean energy due to no emissions of exhaust gases to the environment ([4], [5], [6]).

A solar tower is another way to convert solar energy into electricity. A solar tower is a tall chimney in which a warm air is flowing upward. Flowing air carries kinetic energy, so it can be converted into electricity via a wind turbine mounted inside chimney across air flow. Here, the air at the bottom of the chimney is heated by sunlight under a cover surrounded the tower. The warm air has low density than the air surrounding the system so it is forced upward in the tall chimney due to the gravitational effect ([7], [8], [9]).

In addition to these methods, there are some other methods under investigation to convert solar energy into electricity or to obtain fuel directly through photosentesis or living bacteria organisms. It is seen that the method described above to convert solar energy into electiricity is most cost effective and less efficient one. So as to find an efficient and less costly conversion method is the main purpose of this investigation to be performed.

1.1. Carnot Heat Machine

Here, firstly, a heat machine conversion process is introduced by the Carnot cycle. The heat machine based on Carnot cycle is called Carnot heat machine. Carnot heat machine consists of a piston-cylinder mechanism. Here, heat supplied from a high thermal resource is converted into mechanical energy by the heat machine mechanism which includes a piston motion in a cylinder through a gas expansion process. Carnot cycle consists of four state changes. Two state changes are at constant temprature and the other two are adiabatic. Carnot Cycle is a closed cycle, so there is no gas exchange between the system and environment.

Carnot set has an upper bound for thermal efficiency of any heat engine through four reversible state changes occurance. A reversible process can be described as the system ability to turn to its first state when undergiong a cycle by not leaving any influence on the environment. State changes of an actual heat machine cycle are not the same as the reversible ones since the state changes include irreversiblities. A Carnot heat machine becomes reversible with the assumptions made below.

- Carnot cycle includes two adiabatic state changes, so there is no heat loss from the system

- State changes are carried out quasi-statically; and piston movements are frictionless

Fig. (1) indicates the four state changes of the reversible Carnot heat machine. The cycle state changes can be described as

1-2 heat gain from a high thermal resource during an isothermal expansion (T_H)

2-3 heat transfer side is insulated, system is released to free, continue to expansion

3-4 insulation is removed and heat is ejected to a low thermal resource at constant temperature

4-1 heat transfer side is insulated again; and boundary work is applied on the system to increase temperature from T_L to T_H.

A reversible Carnot cycle is a cycle that can not be measured experimentally. It is an ideal cycle. In Carnot cycle, there is a boundary work produced by the system during expansion and a boundary work on the system during compression, so the net work output of the cycle is equal to the net heat gain of the cycle.

$$W_{net} = Q_H - Q_L \tag{1}$$

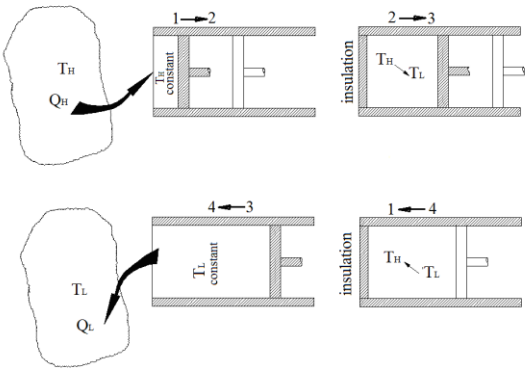

Figure 1. Reversible Carnot Heat Machine Cycle

Here, Q_H is the heat quantity transfer to the system from high thermal resource and Q_L is the waste heat quantity ejected to the low thermal resource in one cycle time at both. So the thermal efficiency of the reversible Carnot heat machine can be defined as below.

$$\eta_{th} = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_H} \tag{2}$$

Here, the thermal efficiency depends on the temperatures of the thermal resources. High temperature difference between both means high thermal efficiency.

2. A SOLAR HEAT MACHINE MECHANISM

Here, a solar heat machine is considered to convert solar energy to potential energy via compressed air. It works like Carnot heat machine since it consists of a piston cylinder machanisms. The state changes of that machine are not reversible since it is an actual heat machine. Here, the aim is to store the solar energy as potential energy inside the air compressed to a storage tank by the mechanical work supplied by the solar heat machine. So, the machine is named as solar heat machine. The energy conversion process in that machine is carrried out by two steps. First, solar energy is converted into heat energy, then to mechnical work to move the piston. In the machine, high thermal source is the absorber plate of the solar collector integrated with the heat machine mechanism. Here, the heated absorber plate by the sunlight heats the air in the solar collector. Owing to the heat gain, air wants to expand, so it exerts pressure to the piston combined with heat machine as shown in Fig. 2; and the consequent stage is the expansion process causing piston movement. By this way, the heat produced by the machine makes mechanical set work. The work produced by the heat machine can be utilized to compress the ambient air to a storage tank by actuating the piston cylinder on the other side of the piston cylinder mechanism. It is called double actuated piston cylinders. Here, the machine is utilized as the solar energy conversion machine by getting the solar radiation to heat energy then to mechanical energy and then to a potential energy of the air compressed. The process described here creates a cycle. For the second cycle to be performed the warm air in the solar collector is exhausted to the atmosphere and the fresh atmosphere air fills the space of the solar collector simultaneously. The heat machine is an open cycle which works according to the steady state open system. Fig. (2) depicts a two dimensional sketch of the solar heat machine mechanism.,

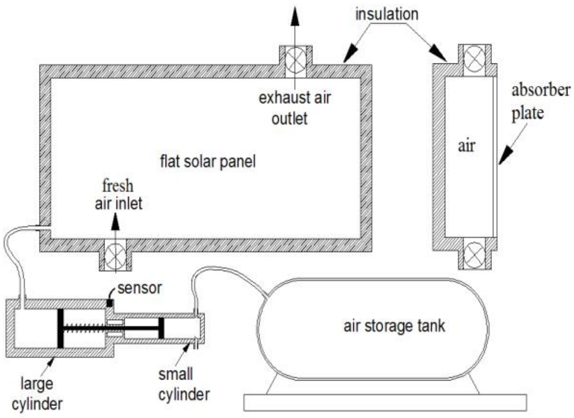

Figure 2. Solar Heat Machine Assembly

The solar heat machine cycle, while resembling to Carnot cycle, has some differencess with it, and can be described as below:

- the state changes are irreversible since friction exists during piston movements
- cycle fluid is refreshed with ambient air at each cycle end while in Carnot cycle is not
- system boundary is insulated, but is not exactly adiabatic, so the heat loss might occur
- no isothermal process during heat gain since pressure and temperature increase during expansion process,

and also a similarity can be set between both as the follows:

- both machines work between high and low thermal energy resources. In the solar heat machine, the absorber
- plate is the high thermal energy source and the surrounding air is the low thermal energy source.
- the expansion process of the solar heat machine is predicted as being performed quasi-statically as the same in the reversible one.
- the working fluid is air in both

As Fig. 2 illustrates, sun light heats the absorber plate and the absorber plate heats the air in the solar collector space simultaneously. The air gaining heat wants to expand, so it exerts pressure to the large piston. As the large piston moves, the ambient air filling the small cylinder space is compressed by forward movement of the small piston. During expansion process, the air gains heat from the absorber plate so that the pressure and temperature of the air will rise until the pressure of the embient air is equal to the pressure of the air in the storage tank, then a check valve opens the way and the pressurized ambient air flows into the air storage tank. The expansion process continues until one piston contacts with the caution stop and there a contact sensor ends the expansion process by opening the exhaust air valve at top of the solar collector. As the warm air is exhausted, the fresh ambient air flows into the solar collector space as soon as the valve at the bottom opens. For a while, these valves are let open by two tempeture sensors one of which is placed at the exhaust gas outlet and the other one is placed at fresh air inlet to ensure that all warm air is exhausted since the temperature difference between ambient air and warm air is a sign to ensure that all warm air is exhausted from the system. As the temperature difference is minimised or becomes zero, an electrical signal to actuator closes the space valves; then, a new cycle begins. In the next section, a theoretical aproach has been developed for the solar heat machine.

3. A THEOERETICAL APPROACH

3.1 An Actual Solar Heat Machine

Compression of the ambient air to the storage tank corresponds to a politropic process since some heat loss can occur in the small cylinder surface. These heat losses cool the air during compression process and by this way, the required compression work reduces. According to the politropic process, the pressure of the ambient air under compression corresponds to the Eq. (3) as given below ([10]).

$$\frac{P_s}{V^n} = C \tag{3}$$

Here, C is a constant, P_s is the absolute pressure of the ambient air, V is the volume of air under compression and n is between $1 < n < k$ where k is the specific heat ratio of the air ($k = 1.4$). While the small piston is in compression, the large piston is in expansion process, so the absolute pressure of air in expansion can be obtained by setting a force balance between both piston areas. Knowing that the piston moves at constant velocity, the pressure force at small piston area can be equated statically to large piston area as given below.

$$F_l = F_s \quad \Rightarrow \quad P_l\,A_l = P_s\,A_s \quad \Rightarrow \quad P_s = \frac{C}{V_s^k}$$
$$\Rightarrow \quad P_l = \frac{C}{V_s^k}\,\frac{A_s}{A_l} = \frac{C}{V_s^k}\left(\frac{D_s}{D_l}\right)^2 \tag{4}$$

Where A_s, A_l is the small piston area and large piston area, respectively, and D_s, D_l is the small and large piston diameters, respectively also. V_s is the volume of the ambient air inside the small cylinder under compression. During the expansion process of the air in large cylinder, the expansion pressure (P_l) rises according to Eq. (4). The thermal efficiency of the machine cycle can be defined according to the heat machine efficiency expression.

$$\eta_{th} = \frac{W_{net}}{Q_H} \tag{5}$$

where,

Q_H : the amount of heat transfered from the absorber plate to the air during expansion

W_{net} : the net work output of the cycle and, here, it is equal to the boundary work of the cycle, expansion process.

The heat machine can be well insulated so that the heat loss from the heat machine during one cycle time can be ignored then the heat transfered to the air during one cycle time can be equated as follows:

$$Q_H = Q_L + W_{net} \qquad (kJ) \tag{6}$$

Q_L is the waste heat of the heat machine that is not converted into the useful work in one cycle time. The waste heat amount can be determined from the relation given in Eq. (7) which represents the energy difference between the air intake and the air exhausted.

$$Q_L = Q_{ex} = m_{ex}\,C_p\,(T_{ex} - T_o) \tag{7}$$

where m_{ex} is the mass of the air in expansion process, C_p is the mean specific heat ratio of the air at constant pressure at a mean temperature between the atmosphere air and exhaust air temperatures and T_o is the temperature of the embient air.

The net work output of the cycle is equal to the boundary work of the expansion process, and knowing that the boundary work supplied is utilized to compress the ambient air to the storage tank then the boundary work of the heat machine must be equal to the compression work of the politropic process. The work required in politropik compression process can be calculated through the relation below as given in Eq. (8) ([10]).

$$W_{net} = W_c = m_s\,\frac{n\,R\,T_o}{n-1}\left[1 - \left(\frac{p_c}{P_o}\right)^{(n-1)/n}\right] \tag{8}$$

where,

m_s : mass of the embient air compressed in one cycle time

P_c : the pressure of the embient air at the end of the compression process, it is equal to the pressure of the storage tank

P_o : pressure of the atmosphere air

R : gas constant of air

The work output of the solar heat machine can easily be determined through Equ (8) since all the parameter in Eq. (8) are measurable quantities. If Eq. (8) and Eq. (7)

are introduced into Eq.(5), then the thermal efficiency of the heat machine can be rated as below:

$$\eta_{th} = \frac{W_{net}}{Q_H} = \frac{m_s \dfrac{n\,R\,T_o}{n-1}\left[1-\left(\dfrac{p_c}{P_o}\right)^{(n-1)\,/\,n}\right]}{m_{ex}\,C_p(T_{ex}-T_o)+m_s \dfrac{n\,R\,T_o}{n-1}\left[1-\left(\dfrac{p_c}{P_o}\right)^{(n-1)/n}\right]} \qquad (9)$$

According to the relation given in Eq. (9), the only unknown parameter in relation is the temperature of the air exhausted (T_{ex}). However, the exhaust air temperature can be computed from the ideal gas relation as given below:

$$P_{ex}\,V_{ex} = n\,R_u\,T_{ex} \qquad (10)$$

Where, V_{ex} and P_{ex} is the volume and pressure of the air at the end of expansion process, respectively and n is the mol number of the air exhausted. By setting a force balance between large piston and small piston area, the exhaust air temperature can be defined in terms of the absolute pressure at the end state of air in compression process.

$$P_l\,A_l = P_s\,A_s \quad \Rightarrow \quad P_l = P_{ex}\,, \quad P_s = P_c$$

$$P_{ex} = P_c\,\frac{A_s}{A_l} \qquad P_{ex} = P_c\left(\frac{D_s}{D_l}\right)^2 \qquad (11)$$

If the relation obtained for P_{ex} in terms of P_c is substituted into the Eq. (10) and then arranged the resulting equation for the exhaust air temperarature, then existed new equation will be as follows:

$$T_{ex} = \frac{P_c\,V_{ex}}{n\,R_u}\left(\frac{D_s}{D_l}\right)^2 \qquad (12)$$

Since all the terms included in Eq. (12) are measurable quantities; hence the temperature of the air exhausted can be computed easily from the relation given in Eq. (12). By knowing the air exhaust temperature, it is possible to determine the thermal efficiency from Eq. (9).

The thermal efficiency of the heat machine defined in Eq. (9) is based on the heat transfer *(Q_H)* rate from the absorber plate to the air. However, this efficiency does not reflect the actual efficiency of a solar heat machine since it must stand on the total solar radiation reaching the absorber plate and how much of it can be coverted into the useful work by the solar heating machine. When the computation is evaluated over that energy conversion process, then actual efficiency of the solar heat machine can be defined as the ability of this heat machine to understand at what rate it can convert the solar energy into the useful mechanical work. So, the actual efficiency of a solar heat machine must be named as the solar conversion efficiency. Before getting the definition in mathematical form, the solar radiation falling on the absorber plate must be defined. It is assumed that the rate of the solar radiation energy falling on the plate is constant during one cycle time; here, the assumption made is considered to be true since one cycle time is small enough compared to one hour time of the day. The amount of the solar radiation falling on the absorber plate during one cycle time can be determined via the relation below as given by Eq. (13):

$$E_I = \int_0^t \dot{E}_I\,A_p\,dt = \dot{E}_I\,A_p\,t \qquad (13)$$

Here, A_p is the absorber plate surface area. Consequently, the solar conversion efficiency (η_{sce}) of the heat machine can be defined with the relation given in Eq. (14):

$$\eta_{sce} = \frac{W_c}{E_I} = \frac{m_s \dfrac{n\,R\,T_o}{n-1}\left[1-\left(\dfrac{p_c}{P_o}\right)^{(n-1)/n}\right]}{\dot{E}_I\,A_P\,t} \qquad (14)$$

Here, the only unknown item in Eq. (14) is the cycle time (t). However, getting a theoretical approach to find the cycle time seems a very complicated issue. So, developing a theoretical relation to compute the cycle time is not afforded here so that the cycle time can be left to the next studies to be solveable theoretically. Another approach to determine the cycle time is to perform the experimental or numerical studies. By both performings, the cycle time can be found directly from the measurements obtained.

Here, the efficiencies of a solar heat machine are intruduced theoretically for a flat solar collector; however, when the parabolic solar collectors are concerned, what the efficiencies of the heat machine are appears an uncertain case. However, the situation for the parabolic solar collectors can be solvable since the only difference between a parabolic and flat collector is just the change in surface temperature. Then the relations obtained for the efficiencies of a flat plate absorber can also be used readily for the parabolic solar collector. Here, such a result can be concluded since it is well known that high temperature difference between thermal resources give high thermal efficiency according to the reversible Carnot heat machine; and knowing that the parabolic absorber surface has higher temperature than the flat absorber surface. Threfore, it can be said that the efficiencies of a parabolic solar collector is higher than that of flat solar collector. The subject of next section is about an ideal solar heat machine.

3.2 An Ideal Solar Heat Machine

In this section, the thermal and solar conversion efficiencies of a reversible solar heat machine are approached theoretically for their definitions. The solar heat machine considered here is similar to the actual solar heat machine by converting the solar radiation into mechanical work by a piston cylinder mechanism. The reversible solar heat machine consists of a flat absorber plate, a double actuated piston cylinder mechanism and air compresssion storage tank the same as the actual heat machine include. An ideal solar heat machine can become reversible when the following assumptions are made:

- Solar heat machine is well insulated from the environment except that of the absorber plate so the state changes are carried out adiabatically
- Piston movement is frictionless and
- Expansion process is carried out at a quasi static manner.

An adiabatic, frictionless and quasi-static state changes make the heat machine cycle reversible, so the Carnot principles can be applied. Here, in the reversible solar heat machine, the high temperature source is the plate and lower temperature source is the ambient air the same as being in actual one. First, at the beginning of the cycle, the air and plate are considered to be at the same temperature with ambient air then exposed to sunlight. The temperature of the absorber plate and the air increase until a thermal equlibrium state is reached between coming radiation and the radiation emitted by the absorber plate. From the beginning of the cycle until an equlibrium state is reached, the piston mechanism is locked; and after equlibrium is reached, the piston mechanism is unlocked to begin a reversible expansion process. The reversible expansion process is the same as in the Carnot heat machine one, so during reversible expansion process, the air temperature is the same as the absorber plate temperature. The reversible expansion process is carried out isothermally at constant pressure to produce useful work the same as the reversible Carnot heat machine. Since the reversible Carnot heat machine principle is valid for the solar heat machine, the thermal efficiency of the reversible solar heat machine can be defined as in the following Eq. (15):

$$(\eta_{th})_{rev} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{T_L}{T_p} = 1 - \frac{T_o}{T_p} \tag{15}$$

Here, T_o is the ambient air temperature at the beginning of the cycle and T_p is the plate temperature during expansion process. At the end of expansion, the warm air is exhausted to atmosphere by leaving the space to the fresh ambient air so as to begin a new cycle. If exhaust air temperature is equal to plate temperature ($T_{ex} = T_p$), then the waste heat of the cycle can be determined with the relation given in Eq. (16):

$$Q_L = m_{ex}\, C_p\, (T_p - T_o) \tag{16}$$

The work supplied by the boundary expansion is utilized to compress air into the storage tank, so the work required to compress air into storage tank is equal to the boundary work output of the system. In order that the reversible heat machine can produce a high thermal efficiency, the compression work must be kept at minimum, so this can be simply accomplished with an isothermal compression process. The work required for the isothermal compression process can be determined from the relation given below as in Eq. (17) ([10]):

$$W_b = W_c = m_s\, RT_o \ln\left(\frac{P_o}{P_c}\right) \tag{17}$$

The heat transfer from the absorber plate to the air at one cycle time can be equaled to the sum of the boundary work produced by the cycle and the waste heat of the cycle by gathering Eq. (16) and Eq. (17) together.

$$Q_H = m_{ex}\, C_p\, (T_p - T_o) + m_s\, RT_o \ln\left(\frac{P_o}{P_c}\right) \tag{18}$$

Consequently, the thermal efficiency of the reversible solar heat machine can be defined as the rate of the net boundary work to the net heat transfered from the absorber plate.

$$(\eta_{th})_{rev} = \frac{W_{net}}{Q_H} = \frac{m_s\, RT_o \ln\left(\frac{P_o}{P_c}\right)}{m_{ex}\, C_p\, (T_p - T_o) + m_s\, RT_o \ln\left(\frac{P_o}{P_c}\right)} \tag{19}$$

All the parameters containing in the Eq. (19) are measurable quantities for a given problem except that of the plate temperature (T_p). So that the thermal efficiency can be determined, the temperature of the plate must be known. Here, the temperature of the plate can be determined from the relationship between Eq. (19) and Eq. (15) by equating both.

Here, it is demonstrated that the thermal efficiency of the reversible solar heat machine can be determined through the analytical relation given by Eq. (19). However, what is the solar conversion efficiency of that machine. By knowing that such a question is answered before for the actual heat machine, then the Eq. (14) can be referred for the solar conversion efficiency. In such a case, the solar conversion efficiency must be taken as the rate of the work output of the system boundary expansion to the amount of solar radiation falling on the absorber plate surface in one cycle time.

$$\eta_{sce} = \frac{W_b}{E_I} = \frac{m_s\, RT_o \ln\left(\frac{P_o}{P_c}\right)}{\dot{E}_I\, t} \tag{20}$$

Altough all parameter values contained in Eq. (20) are measurable quantities for a given problem; however, so as to compute the solar conversion efficiency the cycle time (t) must be known. However, a theoretical approach to find the cycle time can be developed, but it appears to be complex one. In order to develop an analytical relation for the cycle time, further studies can be considered.

4. RESULT AND DISCUSSION

Here, in this study, an actual solar heat machine and an ideal solar heat machine are introduced theoretically. Both machines resemble to Carnot heat machine since they perform the same cycle with the piston cylinder mechanism. Two different efficiencies of the solar heat machine are defined as the thermal efficiency and the solar conversion efficiency. The thermal efficiency indicates that how much heat quantity, transfered from the absorber plate, can be converted into mechanical work; and the solar conversion efficiency indicates how much solar energy can be converted into the mechanical work.

Here, both efficiencies are expressed theoretically for both machines are actual or reversible. For the actual solar heat machine, the thermal efficiency and solar conversion efficiency can be defined theoretically through Equ (9) and Equ (14), respectively. For the ideal heat machine, the thermal efficiency and solar conversion efficiency can be defined through Equ (19) and Equ (20), respectively. While the thermal efficiency of both machines can be determined from the relations obtained for a given problem; however, the solar conversion efficiency can not be determined due to the cycle time restriction in the relation while all other parameters contained in the relation are measurable quantities. So it seems that the cycle time can be defined theoretically, that is, the cycle time restriction can be overcomed. However, knowing that so much effort needed to develope a theoretical relation, the cycle time problem can be left to the next studies consideration.

The solar heat machine considered here is integrated with a flat solar collector, so the theoretical relation obtained belongs to it. However, when a parabolic solar collector is concerned instead, what will be its efficiency? Here, in this study, it is demonstrated that both efficiencies of the parabolic solar collector can be determined via the theoretical relations obtained from the flat solar collector. It is also demonstarted that the efficiency of a parabolic solar collector is higher than that of flat solar collector due to high temperature of the absorber surface since high thermal resource creates a higher thermal efficiency.

In this study a theoretical explanation is made for the solar heat machine; and so as to validate the theoretical relations obtained, it is needed to perform further experimental and numerical studies.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors.

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