Thermodynamic analysis of a Solar Thermal Syphon Pump

Kaushalendra K. Dubey [*, a], R. S. Mishra [a], Gopal P. Sinha [b]
[a] Department of Industrial & Automobile Engineering, Delhi Technological University, New Delhi, India
[b] Department of Mechanical Engineering, Sharda University, Gr. Noida, Uttar Pradesh, India

Article Info

Article history:
Received 12 July 2014
Received in revised form
2 August 2014
Accepted 30 August 2014
Available online 15 September 2014

Keywords

Solar Thermal Energy,
Siphon Pump,
Overall Efficiency,
Exergetic Efficiency

Abstract

This paper describes the idea of the development of a solar thermal energy driven pump for lifting of ground water for irrigation as well as for meeting urban supply system. The principles are equally applicable for lifting any liquid, the head being dependent on density of the liquid. This has the potential of saving over 93billion kWh of electrical energy and 3.3 billion litres of diesel (fossil fuel) per year, for India. The invention has been patented. The most attractive feature of the pump is the absence of any moving part, which makes it almost maintenance-free. Syphon action created by water vapour picked-up from the source, lifts the water from the reservoir through the delivery head. This is being demonstrated for the first time. The efficiency of the entire system is also high on account of no moving parts. Solar thermal energy is used to create a pressure higher than the atmospheric pressure, over the surface of liquid to be pumped to height H. The pressure lifts the liquid through a tube dipped below its surface and delivers to head H, determined by additional pressure created through thermal energy and the mass-density of the liquid.

Nomenclature

Aa = aperture area of PTC in m^2
Sc = solar constant in KW/m^2
Pc = pressure created by solar energy in Pascal,
P_A = Atmospheric pressure in Pascal
Ƥ = Mass density of liquid in kg /m^3.
g = acceleration due to gravity in m/s^2.
h = Enthalpy of steam.
H = Discharge height.
m_w = mass flow rate of water in m^3/s.
m_s = mass flow of steam in m^3/s.
V = flow velocity of water in m/s
Hs = friction loss in pipe.
ϕ = Latitude angle of location where system is installed in degree
β = Inclination angle of PTC system from horizontal in degree.
r_r = Rim Radius in meter.
ϕ_r = Rim Angle in degree
f = Focal Distance in meter.
h_p = Parabolic Height in meter.
D = Receiver or Boiler Diameter in meter.
C_R = Concentration Ratio
Ɵ = Incidence Angle in degree.
ω = Hour angle
γ = System Azimuth angle in degree
δ = Solar Incidence angle in degree.
Ψ = Flow exergy of fluid.
τα = Effective Transmission.
Ib = SolarRadiation.(W/m^2)
n = Total no of day in month measured from 1st January.
$\eta_{opto\text{-}thermal}$ = Opto-Thermal efficiency of Siphon system
Rk = Thermal Resistance of Receiver or Boiler Tube
Acond = Effective area of conduction in m^2
€r = Non selective absorber parameter.
Qgen = Heat generated from PTC.
Qreq = Required Heat for steam generation.
$\eta_{thermo\text{-}siphon}$ = Thermal Efficiency of system.
η_o = Overall Efficiency.
η_{SPV} =Solar Photovoltaic panel Efficiency.
η_{pump} = Irrigation pump Efficiency.
η_{CC} = Charge-Controller Efficiency.
η_B = Battery Efficiency.
l = Length
b = Width
t = Thickness
PTC=Parabolic Through Collector.
STSP= Solar Thermal Siphon Pump.
SPVP= Solar Photovoltaic Pump System.

Corresponding Author,
E-mail address: Professor_rsmishra@yahoo.co.in

1. Introduction

Most of the developing countries have large needs of irrigation for meeting their agricultural requirements for food-security. The drinking water requirement also necessitates lifting of ground water to a height ranging from 50 to 200 feet. This requires huge amount of energy which is currently supplied through electricity and fossil fuel based engines. For a country like India the energy consumed for lift irrigation has been 93225.28MU, (in the year 2011), 1MU= 1M kWhr [6].In most of the cases the developing countries are endowed with rich solar energy. Some of it has been used for lift irrigation using photovoltaic panels electrically coupled to a conventional motor pump system, or Stirling cycle based engine coupled through a conventional pump. The potential number of SPV pumps is estimated at 70 million, with extending irrigation support to untapped markets [7]. This work reports the use of direct solar thermal energy for creating pumping action. The uniqueness of this development is that the pumping action requires no moving parts-reciprocating, rotating or expander action. Therefore there is no possibility of wear and tear or lubrication requirement or loss of energy due to friction between moving parts. Siphon action created by water vapour picked-up from the source, lifts the water from the reservoir through the delivery head. This is being demonstrated for the first time. The efficiency of the entire system is also high on account of no moving parts. The flow chart in fig-1 summarises various attempts of using solar energy for pumping action under three broad heads- (i) through generation of electrical energy which is used to drive a conventional motor coupled to rotary or reciprocating pump, (ii) thermal engine using solar energy driving a conventional pump and (iii) utilisation of solar energy for thermo siphon action. An excellent review of the development of solar energy based pumps have been carried out by Y.Wong et al [11].The proposed thermo-siphon pump is a high pressure steam forced pump where there is no limitation of a suction head of less than 34 feet of water, the delivery head is unlimited based on the concentration of solar energy and the aperture area requirement of the solar collector has been worked out in subsequent paragraphs.

A model has been fabricated for proving the concept. This model demonstrates lifting of water through a head of nearly 5 to 10 feet Fig 3, shows a sketch of the parabolic trough collector (PTC) used for concentrating the solar thermal energy.

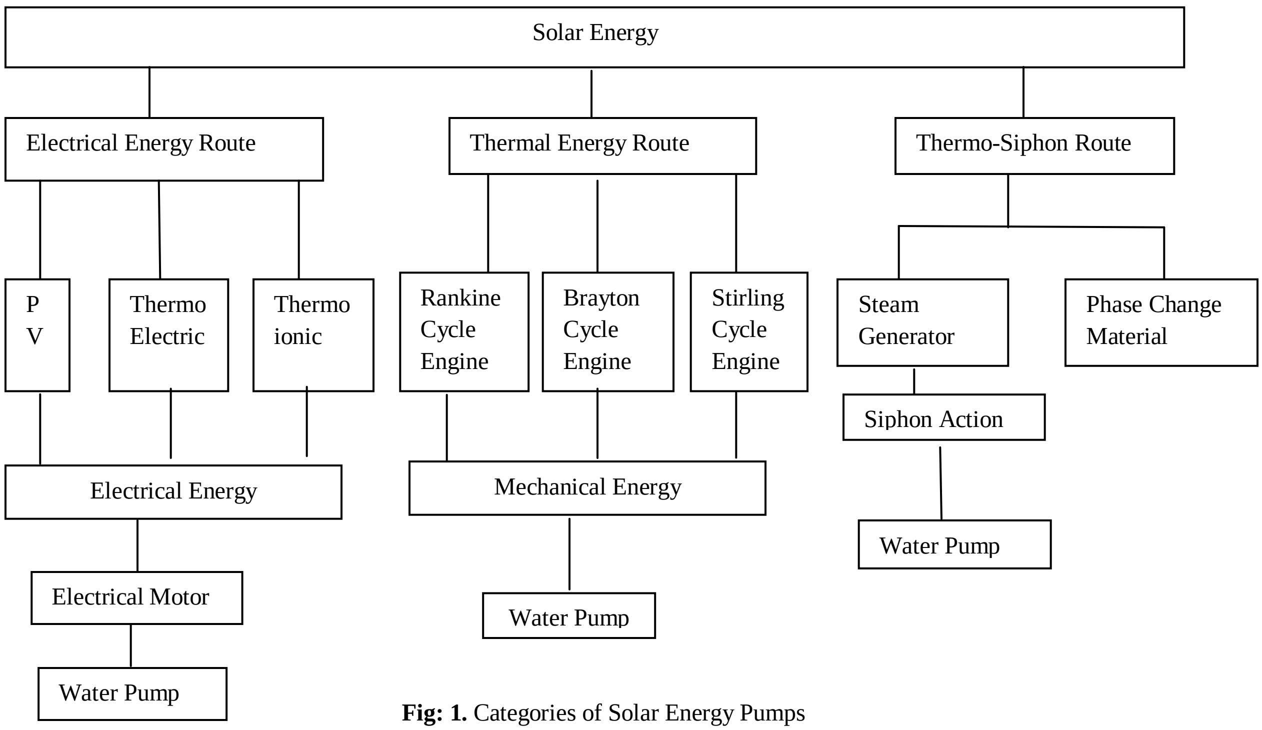

Fig: 1. Categories of Solar Energy Pumps

In most of the developing countries are endowed with rich solar energy. Some of it has been used for lift irrigation using photovoltaic panels electrically coupled to a conventional pump, or Stirling cycle based engine coupled through a conventional pump. The potential number of SPV pumps is estimated at 70 million, with extending irrigation support to untapped markets [7]. Total cost (before subsidy) for installation and commissioning of SPV water pump system varies from Rs. 190,000 to 290,000 or even Rs. 450,000/-[8][9].Capital cost of a 1.8 kWp solar PV pump is about Rs. 0.3 million. The payback period of solar PV pump (without subsidy) replacing a diesel pump is about 9 years (at a cost of diesel is Rs. 32/litre) [10].Purohit evaluated the financial attractiveness of different renewable energy technologies for irrigation water pumping in India. He calculated the following unit costs for water for SVP pumping systems [10].Diesel engine pump sets and Photovoltaic based electric motor pump sets capacities given in Table-1.

Table: 1. SPV based and diesel base irrigation pumping capacities in India [6]

Technology	**Capacity**	**Unit**	**Unit cost for water (without capital subsidy) Rs./m³**	**Unit cost for water (with capital subsidy for S) Rs./m³**
1. SPV pump				
PV pump (surface)	900	Wp	0.85	0.37
PV pump (surface)	1800	Wp	0.83	0.34
PV pump (submersible)	1200	Wp	1.25	0.77
PV pump (submersible)	1680	Wp	1.13	0.65
PV pump (submersible)	1800	Wp	1.17	0.69

2. Electric motor pump				
(Surface)	5	hp	0.38	0.38
(Surface)	10	hp	0.30	0.30
(Submersible)	5	hp	0.39	0.39
(Submersible)	10	hp	0.31	0.31
3. Diesel engine pump set				
(Surface)	5	hp	1.13	1.13
(Submersible)	10	hp	1.02	1.02
Technology	**Capacity**	**Unit**	**Unit cost for water (without capital subsidy) Rs./m³**	**unit cost for water (with capital subsidy for S) Rs./m³**
1. SPV pump				
PV pump (surface)	900	Wp	0.85	0.37

In this context the current work reports about using direct solar thermal energy for creating pumping action. The unique part of this development is that the pumping action requires no moving parts, reciprocating or rotating and therefore there is no possibility of wear and tear or lubrication requirement. A model has been fabricated for proving the concept as shown in Fig 1. This model demonstrates lifting of water through a head of nearly 5 to 10 feet.

2. Working of Solar Thermal Siphon Pump

Solar Thermal Siphon pumping system (STSP) may be used to lift water from the ground or any liquid to a height without using any moving mechanical-part by pressurized steam through siphon action. The steam is generated by solar energy concentrator on a tube filled with the liquid. The concentration of solar energy can be achieved by parabolic trough collector (PTC) / concave / plane mrors type solar concentrator or through Fresnel lenses based solar thermal system.

Water liquid enters into a boiler cell, through an inlet regulated by a float valve action, for maintaining a uniform level. Steam generated in the boiler flows through a perfectly insulated and sealed pipe into an enclosure connected to ground water to be pumped. The discharge pipe is dipped below the ground water. The pressurized steam lifts the water to the delivery head H, through a siphon action. The conversion of water in to steam at boiling temperature of water depends upon the thermal energy obtained from the area of PTC (Aperture Area of concentrator).The heat raise the temperature of boiler and water gets converts into steam. The water feeding pipe use some amount of steam pressure feeding water to the boiler [8]. Fig-2a and Fig-2b show the model and working set up of the thermo-syphon pump. Dimension of all parts of STSP listed in Table-2.

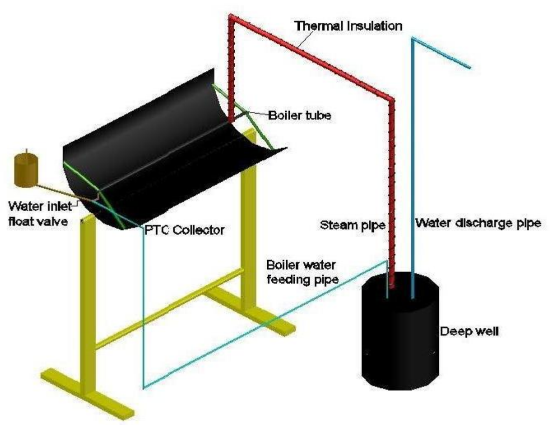

Fig: 2a. Schematic of Solar thermal Siphon Pump

Fig: 2b. Working set up of solar thermal Siphon Pump at Sharda Univ Greater Noida campus

3. Principles of the Solar Thermal Syphon System

The solar thermal siphon pump derives its pumping action by putting additional pressure on the surface of the liquid, to be lifted. This additional pressure is obtained using solar thermal energy in concentrated form.

The concentrated solar thermal energy obtained by a parabolic trough collector (PTC) is given by [2]

$$Q_{gen} = Aa\ Ib\ W \quad \text{...............……... (1)}$$

The useful solar gain by the collector = Qu = Aa (τα) Ib W

τα = Effective Transmission

The head of lifted water or liquid is given by

Volume 2, Issue 3 (2014) 568-573 ISSN 2347 - 3258
International Journal of Advance Research and Innovation

H = (Pc - P_A)/ βg meters .Where Pc is pressure created by solar energy in Pascal, P_A is Atmospheric pressure in Pascal, β is Mass density of liquid in kg /m^3 and g is acceleration due to gravity in m/s^2.

3.1 Collection and Concentration of Solar Thermal Energy using PTC.

For generating steam, whose pressure is used for pumping of liquid to a height, we require concentrated solar thermal energy for super heated high pressure steam at a high pressure. This is achieved by a PTC or a Fresnel lens or a combination of the two. The concentrated thermal energy obtained through PTC is given by Heat required for steam generation [4],

$Q_{reqired} = m_{water} [Cp_{water} (T_{boiling} - T_{ambient}) + LHwater] + m_{steam} [Cp_{steam} (T_{sup} - T_{boiling}) + LH_{vaporisation}]$ KJ ….. (2)

For system to work continuously

Qgen >₋ Qreq ....……………….. (3)

Boiling Temperature of water for the exerting the required steam pressure ($T_{boiling}$) is directly taken from steam table corresponding to the pressure Pc. This heat can generate steam at a pressure Pc is given by

Pressure required on water table for achieving the discharge head

Pc = $10^5 + 10^4$ H Pa ....……..…….. (4)

This pressure on the surface of the liquid can lift it by 'H' meter through siphon action is given by

H = (Pc - Pa)/ βg meter ....…….. (5)

3.2 Estimation of specified head H and flow rate Q

Heat from PTC is mainly required to meet the heat loss occurring due to imperfect insulation and the temperature difference between the superheated steam and the ambient. It is given by,

Total energy in steam = Energy given to discharge

$m_s h = m_w g H + ½ m_w v^2 + hs$ ……..............………...... (6)

Conduction loss in pipe = Effective surface area for conduction (Acond) / thermal resistance (R_k). [1]

$[\frac{(Tr-Ta)}{Rk} \times \frac{Acond}{Aa}]$ ………………….......……….........….. (7)

3.3 Design parameters of PTC.

Parabolic through collector (PTC) are preferred for solar steam generation because high temperature can be obtained without any degradation of collector efficiency. The specifications of PTC shown in figure-2 of PTC design for steam generation. All design calculations provide by equations below.

Projected area for heat require = Aperture area of PTC = Aa m^2

Solar Constant [2] = 1000W/m^2 (Standard for India)

For a designer (including losses), solar constant taken as = 550W/m^2.

Parabolic Aperture area of PTC = Aa m^2 = 550 W / Q_{gen}.

Solar radiation (Ib) = 750W/m^2. (Taken average value for month of April-May)

But area of PTC plate sheet = 1.5 × Aa m^2 (Assume).

Dimensions of PTC on the basis of aperture area, Aa = b × h

Rim Angle [5] = $\phi_r = \sin^{-1} (Aa / 2 r_r)$ ....………. (8)

Focal Distance [5] = f = $\frac{Aa}{4 \tan\frac{\varphi r}{2}}$ ..…......................…….. (9)

Parabolic Height [5] = h_p = f

Receiver or Boiler Diameter [5] = D = $\sqrt{\frac{4}{1000\ \pi\ b}}$ m … (10)

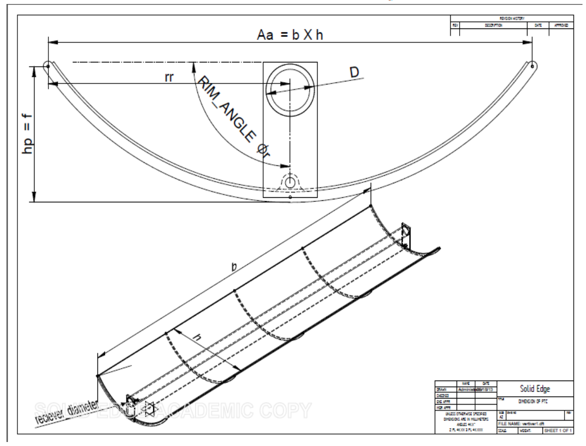

Fig: 3. Schematic of parabolic through collector.

Concentration Ratio [5] = $C_R = \frac{Aa-D}{\pi D}$ ....…….…. (11)

Incidence Angle (ϴ) [2] = Cos ϴ = Sin ϕ (Sin δ * Cos β + Cos δ* Cos γ * Cos ω * Sin β) + Cos ϕ (Cos δ * Cos ω * Cosβ –Sin δ * Cos γ * Sin β) + Cos δ * Sin γ * Sin ω * Sin ....…….. (12)

ω = Hour angle [2] = (Solar Time – 12:00)15^0.

(Afternoon solar time taken as +ve hour angle, whereas forenoon solar time taken as –ve solar time.)

δ = Solar Incidence angle [2] = 23.45 × Sin $[\frac{360}{365} (n + 284)]$ …….............…………….. (13)

3.4 Dimensions of STSP parts

Table: 2. Dimensions of STSP parts

STSP Parts	Dimensions
Reflector	l = 2.44 m, b= 1.25 m, t= 0.4 m. Aperture Area = 2.44 m^2
G.I Sheet for reflector support.	l = 2.44 m, b= 1.25 m, t= 0.36 m.
Copper Water Tube	L = 2.44m,Diameter = 20mm, Volume = 7.6 ×10^{-5} m^3
PVC Steam Tube	Diameter =14mm, Thermally insulated with glass wool.
Supporting Iron Frame **Arc** **Rods** **Rivets** **Mounting Nut**	No. Of Arc = 5, No of Rods = 3 t = 3 mm, Arc length = 1.25 m t = 3mm, l = 2.44 m 10 (Aluminium with head), l = 10mm, diameter = 4mm. Diameter = 9mm (5mm from top and each side)
Iron Stand	l = 1.17 m, t = 5mm.

4. Efficiency involved

4.1 Opto-Thermal Efficiency ($\eta_{opto-thermal}$)

$\eta_{opto-thermal}$ =qu / Ib Aa = $\eta_O - \frac{1}{Ib}[\frac{(Tr-Ta)}{Rk} \times \frac{Acond}{Aa}] + \epsilon r [\frac{Tr4-Tc4}{CR}]$ ………………….....……….……..(14)

Rate of use full energy = $q_u = \eta o\ I_b\ Aa - U_L (Tr - Ta)Aa$ ………….. (15)

Rk = Thermal Resistance of Receiver or Boiler Tube =

$$\frac{\text{Distence Travel by conductive heat in boiler tube or recevier } (x)}{\textit{Thermal conductivity of recevier metal } (K) \times \textit{Condution Area } (A)}$$

4.2 Thermal Efficiency ($\eta_{\text{thermo-syphon}}$)

$\eta_{\text{thermo-syphon}}$ or η_I = $Q_{required} / Q_{gen}$ … (16)

4.3 Over All Efficiency (ηo)

$\eta o = \eta_{\text{opto-thermal}} \times \eta_{\text{thermo-syphon}}$ … (17)

5. Exergy Balance of solar thermal syphon system

Exergy of a Flow Stream per unit mass

A flowing fluid has flow energy; that is the energy needed to maintain flow in a pipe or line;

$w_{flow} = Pv$ ……………………..……… (18)

The flow work is the boundary work done by a fluid on the fluid downstream. The exergy associated with flow energy can be written as

$\Psi_{flow} = PV - P0V = (P - P0)\, V$ ……………….……….. (19)

The exergy of a flow stream can be found from:

The general energy and exergy balance can be expressed in the rate form [12]-

$\sum \dot{\Psi}_{in} - \sum \dot{\Psi}_{out} = \sum \dot{\Psi}_{dest}$ …..…….…….. (20)

$\Psi_{heat} - \Psi_{work} + \Psi_{mass\ in} - \Psi_{mass\ out} = \Psi_{Dest}$ …….. (21)

Using above equation 20 and 21 therate form of the general exergy balance can be expressed as follows:

$\sum \left(1 - \frac{\dot{T}o}{Ts}\right) Qu - \dot{W} + \sum \dot{\Psi}_{mass\ in} - \sum \dot{\Psi}_{mass\ out} = \Psi_{Dest}$ …….. (22)

Where $\Psi_{in} = \dot{m}\, [((h_1 - h0) - T0\,(s_1 - s0) + \mathbf{V_1}^2/2 + gz_1)]$ ……. (23)

$\psi_{out} = \dot{m}\, [((h_2 - h0) - T0(s_2 - s0) + \mathbf{V_2}^2/2 + gz_2)]$…..…. (24)

Due to same elevation of inlet-outlet of flowing fluid = Z_1 = Z_2.

$(1-\frac{To}{Ts})Q_u - \dot{m}[(h_{out} - h_{in}) - To\,(S_{out} - S_{in}) + (\frac{V2^2 - V1^2}{2})] = \psi_{Dest}$ .... (25)

The change in the enthalpy and entropy of water in the copper water tube is expressed as

$\Delta h = h_{out} - h_{in}$ .... (26)

$\Delta S = S_{out} - S_{in}$ .... (27)

The exergy efficiency of a solar thermal siphon system can be calculated in terms of the net output exergy of the system or exergy destructions in the system.

$\psi_{Dest} = To\,(S_{out} - S_{in})$ .... (28)

$\eta_{II} = \frac{\dot{m}[(h\ out - h\ in) - To\,(S\ out - S\ in)]}{(1-\frac{To}{Ts})Qu}$ ....(29)

6. Estimation of STSP efficiency with Photovoltaic pump efficiency.

Efficiency of Solar Photovoltaic Pump (η_{SPVP})

$\eta_{SPVP} = \eta_{SPV} * \eta_B * \eta_{CC} * \eta_{pump}$ .... (30)

$\eta_{SPV} = 15\%$

Above equations taken from ref no [2]

$\eta_{pump} = 50\%$

$\eta_{CC} = 90\%$

$\eta_B = 85\%$

Lead-acid batteries typically have columbic efficiency of 85% and energy efficiencies in order of 70 % [9]. Columbic efficiency is the ratio of number of charges that enter the battery during charging compared to the number that can be extracted from the battery during discharging [9].

η_{CC} depend on the input-output level of voltage-current. DC-AC conversion efficiency as 100% but practically it is not possible because some account of heat dissipated by the passive components. Therefore, there is no way to simulate 100% charge-controller efficiency. We can assume more than 90%.Farm irrigation pumping is around 70 to 80% of total farm electricity usage [10].

$\eta_{overall\ SPVP}$ = 15% * 85% * 90% * 70% = 8.08 %

7. Results and Discussion.

An experiment with the fabricated model was carried out in the month of April-May. In a mid day when the sun rays were focused on the copper boiler, the pump lifted the water from the down reservoir and sprayed a stream up to a required height. The concept was clearly demonstrated.

The result of energy and exergy analysis of STSP shown in table no 3:

Table: 3. STSP Efficiency results

System/Efficiency (%) ↓	$\eta_{optical}$ →	$\eta_{thermal}$ or η_I	$\eta_{overall} = \eta_{optical} \times \eta_{thermal}$	$\eta_{exrgetic}$ or η_{II}
STSP	75	46.6	34.9	10.1

8. Conclusion

It is possible to use direct solar thermal energy for pumping action instead of going through the photovoltaic electrical route, where the overall efficiency of SPV based pumping system comes to 8% against 35-36% of solar thermal siphon pump system. Thus there is a gain of almost 450% in the utilisation of solar energy. Apart from this significant gain in utilisation of solar energy, there is further indirect savings in energy required for production of solar photovoltaic panel. STSP exergetic efficiency is more than $\eta_{overall\ SPVP}$, it conducted that the proposed solar thermal siphon pump would be a significant environment friendly attempt for harnessing solar energy compare to photovoltaic based solar system. The unique part of this development is that the solar thermal siphon pump has no moving parts and it is thus maintenance free.

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