DESIGN AND STUDY OF A SOLAR THERMAL SYPHON PUMP

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ABSTRACT

This paper describes the idea and the development of a solar thermal energy driven pump for lifting of ground water for irrigation as well as for meeting urban supply system. 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. 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 estimated thermal efficiency of solar thermal syphon pumping is four times of photovoltaic pumping system.

Keywords - Solar Thermal Energy, Syphon Pump, Overall Efficiency.

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

ϴ = Incidence Angle in degree.

ω = Hour angle

γ = System Azimuth angle in degree

δ = Solar Incidence angle in degree.

n = Total no of day in month measured from 1st January.

$\eta_{opto\text{-}thermal}$ = Opto-Thermal efficiency of Syphon system

Ib = Solar Irradiation

q_u = Rate of use full energy in joule

U_L = heat loss co-efficient (W / m^2k)

Tc = Receiver Temperature in ^{0}C

Tr = Mean Receiver Temperature in ^{0}C

Ta = Ambient Temperature in ^{0}C

Rk = Thermal Resistance of Receiver or Boiler Tube

Acond = Effective area of conduction in m^2

€r = Non selective absorber parameter.

$\tau\alpha$ = Effective Transmission.

Qgen = Heat generated from PTC.

Qreq = Required Heat for steam generation.

$\eta_{thermo\text{-}syphon}$ = 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 Syphon Pump.

SPVP= Solar Photovoltaic Pump System.

I. 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. 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. An excellent review of the development of solar energy based pumps have been carried out by Y.Wong et al [11].The proposed thermo-syphon 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.

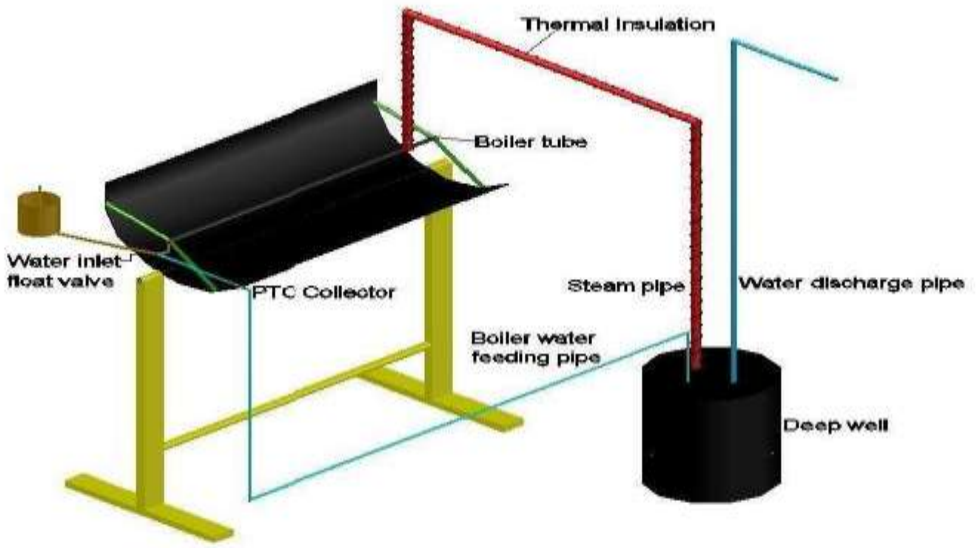
A model has been fabricated for proving the concept. This model demonstrates lifting of water through a head of nearly 5 to 10 feet Fig.2, shows a sketch of the parabolic trough collector (PTC) used for concentrating the solar thermal energy.

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) [12].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]. 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.1a and Fig.1b. This model demonstrates lifting of water through a head of nearly 5 to 10 feet.

II. WORKING OF SOLAR THERMAL SYPHON PUMP.

Solar Thermal Syphon 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 syphon 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 mirrors 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 enclosures 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 syphon 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.1a and Fig.1b, show the model and working set up of the thermo-syphon pump. This system has been developed in mechanical



engineering department sharda university greater noida,u.p. state, India. Dimension of all parts of STSP listed in Table-1

Fig. 1a: Schematic of Solar thermal Syphon Pump.

Fig. 1b: Working set up of Solar thermal Syphon Pump at Sharda University Greater Noida campus.

III. PRINCIPLES OF THE SOLAR THERMAL SYPHON SYSTEM.

The solar thermal syphon 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]

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

The useful solar gain by the collector $Qu = Aa\ (\tau\alpha)\ Ib\ W$

$\tau\alpha$ = Effective Transmission

The head of lifted water or liquid is given by

$H = (Pc - P_A)/\ \beta g$ 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],

$$Q_{required} = m_{water}\ [Cp_{water}\ (T_{boiling} - T_{ambient}) + LH_{water}] + m_{steam}\ [Cp_{steam}\ (T_{sup} - T_{boiling}) + LH_{vaporisation}]\ KJ \quad \text{……………(2)}$$

For system to work continuously

$Qgen \geq Qreq$ ………………………………………………………………………………..(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 syphon action is given by

$H = (Pc - Pa)/\ \beta g$ 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).

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

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

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

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

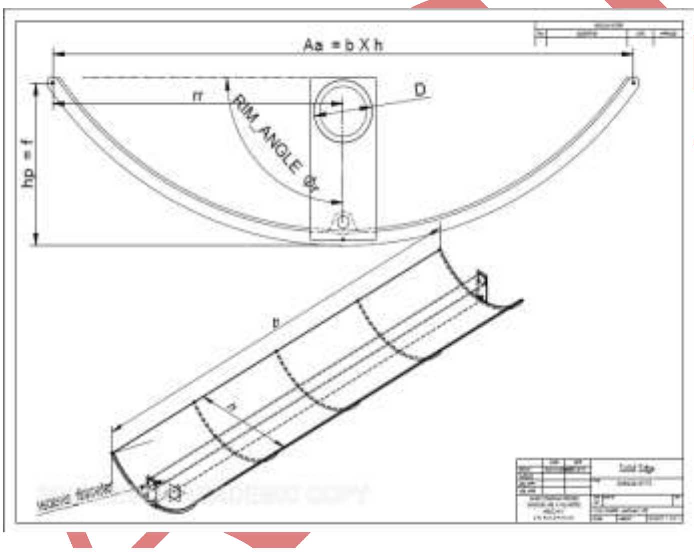


Fig. 2: Schematic of parabolic through collector.

Rim Angle [5] = ϕ_r = Sin^{-1} (Aa /2 r_r)……………..……………………………………………….(8)

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

Parabolic Height [5] = h_p = f

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

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 β……………….(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-1 Dimensions of STSP

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.

IV. EFFICIENCY INVOLVED.

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

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

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

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

$\eta_{\text{thermo-siphon}}$ 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)

V. ESTIMATION OF STSP EFFICIENCY WITH PHOTOVOLTAIC PUMP EFFICIENCY.

Efficiency of Solar Photovoltaic Pump (η_{SPVP})

$$\eta_{SPVP} = \eta_{SPV} * \eta_B * \eta_{CC} * \eta_{pump}$$

η_{SPV} = 15%

η_{pump} = 50%

η_{CC} = 90%

η_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].

η_{SPVP} = 15% * 85% * 90% * 70% = 8.08 %

VI. 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 height of 10 feet. This gave a feel that about 50% of energy was lost in reflector. A more reflective surface with better focussing power is recommended. The concept was clearly demonstrated.

The result of energy and exergy analysis of STSP shown in Table 2:

Table-2, STSP Efficiency results

System/Efficiency (%) → ↓	$\eta_{optical}$	$\eta_{thermal}$ or η_I	$\eta_{overall} = \eta_{optical} \times \eta_{thermal}$
STSP	75	46.6	34.9
SPV Pump			8.08

VII. CONCLUSION.

It is possible to use direct solar thermal energy for pumping action instead of going through the photovoltaic electrical route, where the SPV pumpinjg system overall efficiency comes to 8% against 35 % (η_{opt} and η_I comes 75% and 46% respectively) of solar thermal syphon pump system. Apart from this significant gain in utilisation of solar energy, there is further indirect savings in energy required for production of solar photovoltaic panel. The solar thermal syphon pump would be a significant environment friendly attempt for harnessing solar energy.

The unique part of this development is that the solar thermal syphon pump has no moving parts and it is thus maintenance free.

VIII. ACKNOWLEDGMENT

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