International Journal of Energy and Power Engineering
2015; 4(3): 184-188
Published online June 24, 2015 (http://www.sciencepublishinggroup.com/j/ijepe)
doi: 10.11648/j.ijepe.20150403.17
ISSN: 2326-957X (Print); ISSN: 2326-960X (Online)

Energy Efficiency and Cost Effectiveness of Solar Water Heaters

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To cite this article:
Zohrab Melikyan. Energy Efficiency and Cost Effectiveness of Solar Water Heaters. *International Journal of Energy and Power Engineering*. Vol. 4, No. 3, 2015, pp. 184-188. doi: 10.11648/j.ijepe.20150403.17

Abstract: There are different opinions on the question of energy and economic efficiency of solar water heaters. Some researchers believe in high effectiveness of solar water heater application while others questions their cost effectiveness. In this article detailed investigations have been accomplished to discover energy and economic real efficiency of different types of solar water heaters on the base of suggested procedure for their real payback periods determination. It's proved that flat type solar water heater has much longer payback than newly suggested cylindrical shell and tube type solar water heater.

Keywords: Cylindrical Shell-and-Tube Type Solar Water Heater, Energy and Economic Efficiency

1. Introduction

Analysis of literature data shows that in last a few years the costs of solar water heaters became noticeably cheaper. However, according to American sources [1,2], at present the prices are in the range $800 to $10 000 depending on their types. The cheapest are flat type solar water heaters. The costs of professionally produced plants vary from-$3500 to $6000. For instance, the researchers of American National Laboratory of renewable energy (NREL)[3] accomplished detailed analysis to evaluate the initial cost of simplest construction of a flat type solar water heater. It was disclosed that for providing domestic hot water for a family of three members flat type solar water heater with sizes 1.8 m by 2.4 m is quite enough. The researchers assert that such flat solar water heater with surface 4.3 m^2 is able to prepare 120 liter of hot water heated from 10°C to 43°C. However, they give notice that only 75% of 120 liter of water can be heated by the solar energy. The rest of the water, that is to say 30 liter, should be heated by a supplementary gas or electric heater.

Analysis of NREL allow concluding that initial cost of such a small, low power flat type solar water heater of such a simple construction makes at least $1000.

The researchers supplement, that payback period of mentioned flat type solar water heater makes 2.5 to 3.4 years.

It seems there is some error in assessment of payback period, as 3.4 years is too short term.

Perhaps the annual operational cost of gas or electricity consumption for supplementary heating of 30 liter deficit of water from 10°C to 43°C was not included into account. To prove the incorrectness of such assertion the author of this article executed his own investigation.

2. Investigation of Energy and Cost Effectiveness of Simple Construction of Flat Type Solar Water Heater

Trying to finding out the real payback period of flat type solar water heaters energy and economic analysis were accomplished [4]. Supplementary heating of 30 liter of water deficit per day Q_{def}, requires thermal energy which is determined by the following formula [5]:

$$Q_{def} = G_{w.def} c_w \left(t_{hot} - t_{cold} \right), \qquad (1)$$

where:

$G_{w.def}$ = 30 kg/day - daily quantity of deficit water,

c_w = 4.18 kJ/kg°C – specific heat of water [6],

$(t_{hot}-t_{cold})$=33°C - difference of final and initial temperatures of heated water.

According to formula (1) the quantity of daily deficit of thermal energy makes the following value:

Q_{def}=30·4.18·(43-10)=4138.2 kJ/day or

Q_{def}=4138.2/3600 = 1.15 kWh/day.

If mentioned above deficit of heat is covered by high efficiency gas booster boiler operating with COP=0.8÷0.85, it daily consumes a quantity of gas $V_{gas.day}$ (m^3/day) which can be determined by the following ratio:

$$V_{gas.day} = \frac{Q_{def}}{\eta_{gas.h}\, Q_{gas}}, \qquad (2)$$

where:

$\eta_{gas.h}$ = 0.8 - COP of gas booster boiler,

Q_{gas}=9.3kWh/m^3–burning calorific capacity of natural gas.

By the help of formula (2) and above data, the daily consumption of natural gas by gas booster boiler is determined as follows:

$$V_{gas.day} = \frac{1.15}{0.8 \cdot 9.3} = 0.155 \text{ m}^3\text{/day.}$$

The gas consumption $V_{gas.seas}$, during summer season by the boiler for covering thermal energy deficit, is determined by the following production:

$$V_{gas.seas} = V_{gas.day} \cdot Z_{seas}, \qquad (3)$$

where:

Z_{seas} – number of summer season's sunny days with appropriate temperatures.

The number of summer season's sunny days with appropriate temperatures Z_{seas}, for instance in the city of Yerevan, Armenia located in 40^o latitude, makes Z_{seas} =150 days [7] (within beginning May to end September).

According to formula (3) the seasonal quantity of gas $V_{gas.seas}$, (m^3/seas) consumed by gas boiler makes the following value:

$V_{gas.seas}$=0.155 m^3/day ·150day/seas = 23.3 m^3/seas

The cost of consumed gas U_{gas} (\$/year) during summer season is determined by the following production:

$$U_{gas} = V_{gas.seas.} \cdot C_{gas}, \qquad (4)$$

where:

C_{gas}=0.367 \$/m^3 – tariff of gas, for instance in Armenia.

According to formula (4) the cost of gas U_{gas} (\$/year) consumed seasonally by the gas boiler for covering heat deficit makes the following amount:

U_{gas} = 23.3 m^3/seas · 0.367\$/m^3 = 8.55 \$/seas.

However, alongside with obtained above additional negative expenses U_{gas} should be taken into account the positive benefit, obtained from the use of flat solar water heater. As the solar water heater annually produces useful heat $Q_{usef.seas}$ (kWh/year), by using solar radiation for daily heating of 90 liter of water from 10^{o}C to 43^{o}C, the positive quantity of useful heat $Q_{usef.seas}$ (kWh/seas.) can be calculated by the following formula:

$$Q_{usef.seas} = \frac{G_{w.sol} c_w \left(t_{hot} - t_{cold}\right) Z_{seas}}{3600}, \qquad (5)$$

where:

$G_{w.sol}$ = 90 liter/day – daily quantity of water heated only by solar energy,

3600 – coefficient of conversion of kJ to kWh.

Calculation with the help of formula (5) allows finding the seasonal quantity of useful heat provided by the sun-

$$Q_{usef.seas} = \frac{90 \cdot 4{,}18(43-10) \cdot 150}{3600}$$

or $Q_{usef.seas}$=517.275 kWh/seas.

Consequently the solar water heater allows saving natural gas in quantity determined by the formula as follows [13]:

$$V_{gas.seas} = \frac{Q_{usef.seas}}{\eta_{gas.h.} Q_{gas}},$$

or

$$V_{gas.seas} = \frac{517.275}{0.8 \cdot 9.3} = 69.526 \text{ m}^3\text{/seas.} \qquad (6)$$

The cost of saved gas makes U_{saved}=69.526m^3 · 0.367 \$/m^3 =25.516 \$/seas. Therefore, the annual real cost of saved gas by solar water heater makes only

$U_{real.year}$=25.516-8.55=16.966\$/year,

which is the real benefit from application of the solar water heater. As the capital cost of construction and implementation of flat type solar water heater is K=\$1000, and its annual benefit is $U_{real.year}$= 16.966 \$/year then the payback period *Y*, of capital investment for implementation and maintenance of flat type solar water heater makes:

$$Y = \frac{K}{U_{real.year}} = \frac{\$1000}{16.966\,\$/year} = 58.94 \text{ year.}$$

International experience of application of solar water heaters show that duration of life cycle of solar heaters active use does not exceed 10÷15 years [8]. Therefore, it is clear that costs of savings by flat type solar water heaters are not able to get back the capital cost even during whole life cycle. Summarizing above data brings to the conclusion that application of flat type water solar heaters provide some very little fuel saving, but they are not cost effective, as the payback real periods are too long. The research proves also the impossibility of stated 2.5÷3.4 years very short payback period. From this point of view developing of solar water heaters with low initial cost is a question of vital importance. The author of this article made efforts intended to solve the problem by developing very simple and cheap construction of a cylindrical shell-and-tube type solar water heater [9].

3. Energy Efficiency and Cost Effectiveness of Cylindrical Shell-and-Tube Type Solar Water Heater

The units of shell-and-tube type solar water heater consist of transparent cylindrical shell for instance glass tube, containing metallic tube, mounted inside the shell coaxially and creating narrow air gap between glass tube and metallic tub. The ends of units are hermetically closed by elastic membranes. The water flows through metallic tubes and is heated. The required total length of the cylindrical solar water heater is formed by connecting the units serially with short pieces of rubber hoses. The method of calculation and design of shell-and-tube solar water heater is developed according to principles of solar engineering and optical phenomena of reflections, refractions and penetration of solar rays taking place in cylindrical transparent shell of solar water heater [10, 11, 12].

To evaluating energy efficiency and cost effectiveness of newly developed cylindrical shell-and-tube type solar water heater it is compared with efficiency of flat type one.

It is assumed that cylindrical shell-and-tube type solar water heater because of its higher energy efficiency is able to heat the required 120 liter of water from 10^{o}C to 43^{o}C only by solar energy without help of supplement gas heater. In order to determine the capital cost of cylindrical shell-and-tube type solar water heater which is necessary for energy and economic calculations, first should be found its required length $l_{m.tub}$ (m), which is possible to do by the help of following equation, obtained in [9]:

$$t_{w.fin} = \frac{2A\left(g_w c_w t_{w.in} + 498.35 d_{ext.met.tub.} l_{m.tub}\right) + \pi l\left(2t_{out} - t_{w.in}\right)}{2Ag_w c_w + \pi l}, \qquad (7)$$

For direct revealing of the required length $l_{m.tub}$ (m) of shell-and-tube solar water heater for heating the water to needed final temperature $t_{w.fin}$= 43^{o}C, the equation (7) is converted into the following form:

$$l_{m.tub} = \frac{2Ag_w c_w\left(t_{w.fin} - t_{w.in}\right)}{996.7Ad_{ext.met.tub} + \pi\left(2t_{out} - t_{w.in} - t_{w.fin}\right)}, \qquad (8)$$

where:

g_w-water flow rate in one unit of solar water heater (kg/s),

$t_{w.in}$=10^{o}C –initial temperature of water at the inlet of solar heater,

A - resistance to heat losses, from shell-and-tube solar water heater to outside air (m^{o}C/W),

t_{out} = -19^{o}C– outside air design temperature in Yerevan, Armenia.

The resistance to heat losses A (m^{o}C/W) is determined by the following equation [9]:

$$A = \frac{1}{\alpha_w d_{int.met.tub.}} + \frac{1}{2\lambda_{met}}\ln\frac{d_{ext.met.tub.}}{d_{int.met.tub}} + \frac{1}{2\lambda_{air}}\ln\frac{d_{in.gl.tub}}{d_{ext.met.tub.}} + + \frac{1}{2\lambda_{gl}}\ln\frac{d_{ext.gl.tub}}{d_{int.gl.tub}} + \frac{1}{\alpha_{air.out} d_{ext.gl.tub}}, \qquad (9)$$

where:

α_w=100W/m^{2o}C– coefficient of heat convection on internal surface of metallic tube,

$\alpha_{air.out}$=23W/m^{2o}C– coefficient of heat convection on outside boundary surface of glass tube,

λ_{met}=40W/m^{o}C – coefficient of heat conductivity of metal tube,

λ_{air}=0.027W/m^{o}C –coefficient of equivalent heat conductivity of air in the air gap,

λ_{gl} =0.745W/m^{o}C – coefficient of heat conductivity of glass,

$d_{int.met.tub}$ =0.016m– internal diameter of water metallic tube,

$d_{ext.met.tub}$=0.021m –external diameter of water metallic tube,

$d_{int.gl.tub}$=0.04m– internal diameter of cylindrical glass tube,

$d_{ext.gl.tub}$=0.044m-external diameter of cylindrical glass tube.

Substitute of above given data in (9) and accomplished calculations reveals the value – A=13.61m^{o}C/W. Water flow rate g_w in water metallic tube of the solar heater can be found by the help of formula as follows:

$$g_w = M_{day} / \left(\theta_{day} \cdot 3600\right) \text{ kg/s}, \qquad (10)$$

where:

M_{day}=120kg/day–daily required mass of hot water,

θ_{day} = 9h- number of sunny hours of summer days.

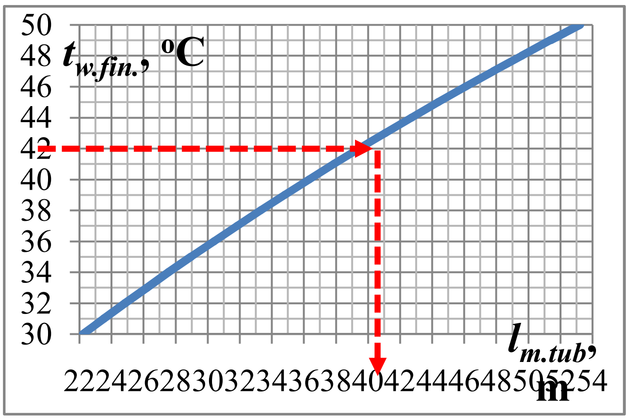

Fig. 1. *Curve of required lengths of shell and tube cylindrical solar water heater depending on different final temperatures $t_{w.fin.}$ of water.*

Using above values the water flow rate g_w=0.0037kg/s of the solar heater was determined. To finding out required total length $l_{m.tub}$ (m), of cylindrical shell-and-tube in case of which $t_{w.fin}$=43^{o}C is provided, by the help of (8) calculation was accomplished assuming that solar water heater is located in Yerevan city (Armenia) characterized with summertime outside air design temperature t_{out}=+35^{o}C and with values of direct and diffused solar radiations daily average intensities: E_{dir}=250W/m^2, E_{diff}= 100W/m^2 [7]. The penetration rate of direct and diffused solar radiations into cylindrical solar heater makes τ_p=0.8836 [9]. By data given above, the required lengths $l_{m.tub}$ of cylindrical solar water heater, were determined using (8), for different final required temperatures $t_{w.fin}$ of water. The fig.1 represents the results of calculations.

Fig.1 shows that required total length of cylindrical solar water heater, for heating of 120 kg/day water up to $t_{w.fin}$= 43°C makes $l_{m.tub}$ =41m. Application of one 41m long solar heater is impossible, that is why it is becoming expedient to convert one long solar heater into moduls, consisted of parallel installed units with length l_{unit}=1.2 m each. From one 41m long tube can be made n_{unit} = 41m/1.2 m = 34 units with lengths 1.2 m each. Composing modules with 7 parallel units, it is possible to make n_{modul}=34/7=5 modules with lengths l_{modul}=1.2 m each as it is shown in fig.2.

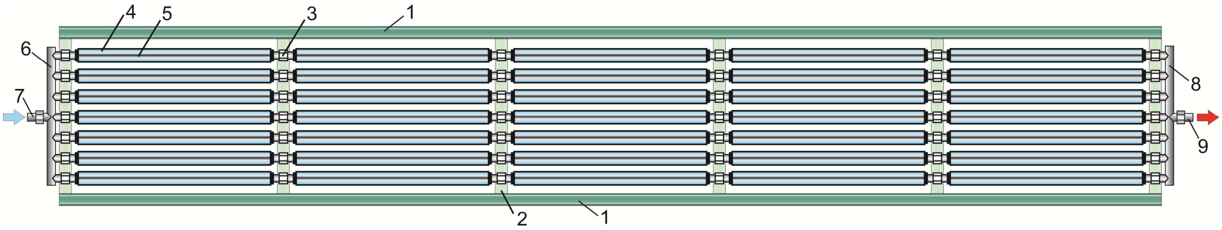

Fig. 2. *Schematic drawing of the array composed of 5 modules of cylindrical solar water heaters.*

1- Metallic frame, 2- metallic supports of units, 3-connections with rubber hoses, 4- glass tubes of cylindrical solar water heaters' units, 5- water heating metallic tubes, 6- collector of supplied tap water with initial temperature tw.in = 10°C, 7- tap water supplying pipe, 8- collector of heated water, 9- hot water pipe to consumers.

In case of such structure the water flow rate in each unit will be g_w=0.00053 kg/s. The 1.2m long modules, joint each other in series, form array. In this mode the total length of array of 5 modules joint in series makes l_{array}=5x1.2=6.0m. The modules are mounted on metallic frame and installed on rooftop or in a free area, near the building. Like flat type solar water heaters the cylindrical water heater is furnished with hot water collecting tank. However, there is no need to mount supplementary electric or gas heater in the tank as in summertime the cylindrical solar water heater is able to heat the completely required 120 liter of water up to 43°C only with sun energy. In order to determining the capital cost of heliosystem consisted of cylindrical solar water heater units all materials, their quantities and market costs, as well as labor cost for constructing, assembling and testing of heliosystem are accounted. The cost of manually fabricated 1,2m long experimental unit of cylindrical solar water heater makes about $5.6 each. The cost of each module with 7 units is $ 39.2, cost of the array of 5 modules makes $39.2·5=$196. The total cost of hot water tank with 120 liter capacity including $440 total cost of its insulation, pump, rubber hose, valves and auxiliary equipment is also added to $196 cost of units. Besides, $100 of labor cost for installation is added. So, the total capital cost of heliosystem assembled with units of cylindrical solar water heater makes: K=$196+$440+$100=$736, while the capital cost of flat type solar water heater of 90 liter per day is $1000 [3].

Comparison shows that the installed heliosystem's cost, referred to 1 liter of 43°C water makes: - for flat water heater $13.3 per liter, while for cylindrical solar heater it is about $6.13 per liter, that is to say twice less. It is natural that in case of mass production the mentioned cost will be lower.

Energy and economic indices of the system are conditioned mainly by its capital cost. The examined heliosystem during its life cycle free of charge produces useful heat Q_{usef}, kW/seas., the quantity of which is determined by (4). Substitution of adequate data for quantities in (4) the following seasonal quantity of useful thermal energy Q_{usef}, kW/per year is obtained:

$$Q_{usef} = 120 \cdot 4.18 \cdot 33 \cdot 150 / 3600\,,$$

or Q_{usef}= 689.7kWh per year.

If producing such quantity of thermal energy by a high efficiency water boiler then will be saved natural gas, the seasonal quantity of which is calculated by the following formula:

$$V_{gas} = \frac{Q_{usef}}{\eta_{boil} \cdot Q_{gas}}\,, \tag{11}$$

Substitute the adequate values in (11) and making calculation the following saving is obtained:

$$V_{gas} = \frac{689.7}{0.8 \cdot 9.3} = 92.7 \text{ m}^3\text{/year}$$

So, developed heliosystem allows saving yearly 92.7 m^3 natural gas the cost of which makes:

$$U = 92.7\text{m}^3 \text{ x } 0.367 \text{ \$/m}^3 = 34 \text{ \$/year.}$$

The results of above investigation shows that the heliosystem of cylindrical shell and tube type solar water heater's capital cost is K=$736 and yearly benefit from its application is U=34 $/year. Therefore, the payback period makes Y=$736/34$/year=21.6 year.

Investigation by applied method proves that the newly developed cylindrical shell and tub type water solar heater is more energy efficient, than at present widely used flat type solar water heaters. Particularly, cylindrical type solar heater saves gas in quantity 92.7 m^3/year, while the annual gas saving of flat type solar water heater makes 62.57m^3, that is to say the gas saving of cylindrical solar water heater in 30.13m^3/year or in 32.5% is more. Payback period of cylindrical shell and tub type water solar heater is shorter in ΔY= 58.97 – 21.6=37.4 year or about in 2.73 times.

4. Conclusions

1. The suggested method for determination of capital and annual operation costs of solar water heaters allows deriving correct values of their energy efficiency and cost effectiveness, as well as their payback periods.

2. Wide implementation of developed cylindrical shell and tub type water solar heaters provide energy and economic higher effect, compared with flat type water solar heaters.

3. If even 70% of residential houses of Republic of Armenia would have been provided with newly developed cylindrical shell and tub type solar water heaters it would be possible to save about 1 973 515 m^3/year of imported expensive natural gas for purchasing of which for instance , Armenia pays 724 280$/year.

4. Wide implementation of developed cylindrical shell and tub type solar water heaters will spur on their line production, creation of many job places and reducing the number of jobless people.

5. Obtained 58.97 year payback period proves incorrectness of presupposed 2.4 ÷ 3.5 years payback for flat type solar water heaters.

6- In spite of sensible advantages nevertheless, at this stage cylindrical shell and tube type solar water heaters would not be very attractive for consumers because of rather long pay-back period. Therefore, more research and technical efforts are needed for their constructive improvements aiming at reduction of capital cost.

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