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ORIGINAL ARTICLE

Thermal performances of non-reversible pressurized and non-pressurized natural convection solar water heating systems using Meander and serpentine turn fluid flow channel absorbers

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Abstract

System performance of a natural convection (thermosyphonic) solar water heater depends on design and setup of collector and storage tank as well as environmental factors such as solar intensity, ambient temperature and wind conditions. The relative height separating the tank and collector mainly influences the magnitude of the thermosyphonic mass flow rates, including both forward and reverse flow at night (during off sunshine hours). In this experimental investigation, meander turns tube solar collector absorbers for pressurized solar hot water systems and parallel tube solar collector absorbers for non-pressurized solar hot water systems and sound theory for preventing reverse flow in free convection solar systems have been established. In this design the outlet of solar collector was connected to an insulated hot water storage tank from the top. The effect of the separation height between tank water level and collectors' top fluid outlet was investigated. Thermosyphonic water mass flow rates (kg/hr) were measured in forward fluid flow direction. The results obtained from developed thermal model have been compared with experimental measured values and found good match between theoretical and experimental results.

1. Introduction

Energy is essential for raising living standards and advancing societal progress. Reliance on traditional fuels must be reduced as a result of their scarcity. This requires a greater reliance on renewable energy sources, such as wind, geothermal, solar, bio-, and hydrogen energy, among others. There are many uses for solar energy, including heating water, drying crops, desalination, heating and cooling buildings and spaces, air conditioning and refrigeration, and the generation of mechanical and electrical power. The most popular use of solar energy is for hot water. Typically, 25% of people on Earth utilize hot water. The amount and trend of hot water consumption vary greatly between nations. The typical daily hot water use in western countries is between 60 to 85 liters per person, it ranges from 25 to 50 liters per person in eastern countries. About 40ºC is the ideal temperature for household hot water. The consumption pattern varies greatly from one location to another. The size of different solar energy system components is determined by a number of physical factors, including local weather conditions and the daily need for hot water. Because of changes in incident solar energy throughout time. The solar energy system should ideally be built with a sufficient storage system to accommodate the ambient temperature. The use for which a solar energy system is typically planned to

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determines the types of thermal energy storage systems. There are essentially two types of thermal energy storage systems such as sensible heat storage and latent heat storage system. The sensible heat storage systems also classified as hot liquid (water/ oil etc) storage and hot air storage systems. The two main forms of water heating systems utilized in homes and businesses are (i) forced convection water heating systems and (ii) natural convection water heating systems [1].

2. Natural convection water heating systems

The flow of liquid in the collector loop of natural convection solar water heating systems is caused by buoyancy forces created by density variations in the fluid inside the collector. These systems often have the tank over the collector and don't require a pump. The occurrence of reverse flow is a frequent issue in these systems, and it has been covered in detail in this study. Only modest systems that are appropriate for home usage can accomplish natural convection.

Under identical meteorological conditions, two commercially available residential pressurized and nonpressurized hot water systems were experimentally investigated. The systems used natural convection, which is maintained by the water flow from the collector to the tank. Numerical calculations utilizing a simplified theory have confirmed the measurements. The mass flow rate of water caused by the thermosiphon effect has been explicitly expressed in terms of known physical characteristics. According to the measurements, the useful energy available from the pressurized and nonpressurized systems is 3.06 kWh and 3.83 kWh per unit collector area, respectively, for an incident solar energy of 6.75 kWh/m^2 of collecting area. This results in a daily average efficiency of 41% and 47% [2,3].

3. Forced convection water heating systems

It is impossible to avoid using a pump to circulate the fluid in the collector loop for large capacity systems. For this reason, these systems are referred to as forced convection systems. Heat exchangers are frequently used in the collector loop of forced or natural convection systems, particularly in cold climates or areas with drinkable water. In the former scenario, it is impossible to avoid using a sufficient amount of antifreeze solution in the collector loop; in the latter scenario, it is recommended to use diminished water in the collector loop to extend the systems' operational life. Despite the fact that thermosyphonic water heating systems have been the subject of numerous studies, there are still a number of issues that need to be resolved. A very simple design process for thermosyphonic solar water heating system sizing by using simple transient thermal model was created to forecast the thermal performance of home solar water heating systems, and performance equations for both sunny and off-sunny hours were independently generated. The mass flow rate of water via the collector and the impact of reverse flow during off-peak hours, with and without demand pattern features of different household applications, are taken into consideration by the transient thermal model. Experimental data on pressurized and non-pressurized solar water heating systems have been compared with the theoretical results. Designing thermosyphonic systems logically is made possible by the derivation of the thermosyphonic mass flow rate of fluid in the collector loop [4].

4. Concept of reverse flow natural convection solar water heating systems

4.1 Phenomenon of reverse flow in natural convection solar water heating systems

Reverse flow can occur in thermosyphonic solar hot water systems during the period of no sunshine hours, especially when the hot water storage tank is located below the collector. Reverse flow, if present in the system can lead to considerable heat losses, if not properly checked. It appears that this effect is not considered by many manufactures of the hot water systems commercially available in the market, which have an average thermal system efficiency of 35% or below should be specially checked for reverse flow, anticipating that these are otherwise well designed as for as collector, tank, piping and insulation is concerned.

To understand the phenomena of reverse flow, in the natural convection solar hot water systems, let us consider solar water heater as a U tube. During the day time, the head of water in the tank plus that of the water in the return pipe constitutes the falling column of water, while the head of water in the absorber and in the flow, pipe constitutes the rising column. The temperature in the return and in the flow, pipe varies with the height and it is thus useful to introduce the concepts of mean density and mean temperature. The mean temperature is defined as

$$T_m = 1/h\ [f(h)dh] \tag{1}$$

Where f(h) is the function describing the temperature at any given height h. Let [$\boldsymbol{\rho_1}$] and T_1 be the mean temperature of water in the right leg of the U tube representing head of water in the tank plus water in return pipe. and [$\boldsymbol{\rho_2}$] and T_2 be the mean density and mean temperature of water in the left leg of the tube consisting of solar collector absorber and the flow pipe. T_1 is normally $\leq T_2$ and hence $\boldsymbol{\rho_1}$ is $\geq \boldsymbol{\rho_2}$ Under these conditions, the left leg of water is no longer able to balance the right leg, which falls continuously, displacing the water from left leg into the tank. The pressure causing the flow in the direction, down the return pipe and up the flow pipe is [H*(density difference)] and is termed as total circulation pressure. If T_2 is $\leq T_1$ * [i.e. density $\boldsymbol{\rho_2}$ at [2] point is greater than density at $\boldsymbol{\rho_1}$ [1] point, then circulation is in the opposite direction i.e. reverse flow, is equally likely. During off sunshine hours, the mean temperature T_2 could be reduced below T_1 in two ways viz (i) insufficient or complete lack of insulation on the flow pipe and (ii) heat losses from the absorber itself. In a well-constructed system, the heat losses from the absorber would be predominant effect and on a cold night the temperature of water in the absorber could be reduced to such a extent that the mean temperature of water in the left leg would be less than the mean temperature of water in the right leg. We know that $[H=(H_1+h_1)]$ if for the right-hand side of the tube, it is assumed that,

T_1= weighted mean temperature over height H
T_t =weighted mean temperature over height h_1 of the water in the storage tank and
T_r=weighted mean temperature over height H_1 of the water in the return pipe.

One can then write

$$T_1=[\{T_r*H_1+T_t*h_1\} / (H_1+h_1)] \qquad (2)$$

Similarly for the left-hand side if,
T_2= weighted mean temperature over height H
$T_{absorber}$ =weighted mean temperature over height h_2 of the water in the solar collector absorber and
T_f=weighted mean temperature over height H_2 of the water in the flow pipe. One can then write following equation.

$$T_2=[\ \{T_f\ (h_1+H_1)+ (T_{absorber} - T_f)h_2\ \}/ (H_1+h_1)\ ] \qquad (3)$$

To prevent the condition of reverse flow, we must satisfy the condition that $T_1= T_2$. Equating therefore expression (2) and (3) and rearranging one gets

$$H_1=[\{\ (T_f - T_{absorber})h_2+ (T_t - T_f)h_1\} / (T_f - T_r)] \qquad (4)$$

Expressed in terms of the difference in height $[h_3]$ between the top of solar collector absorber and the bottom of the hot water storage tank $[h_3] = [H_1-h_2]$ and

$$[h_3] =[\{[\{\ (T_r - T_{absorber})*h_2+ (T_t - T_f)*\ h_1\} / (T_f - T_r)]\ \} - h_2] (5)$$

From equation (5) one can argue that it is unlikely for the flow tobe stopped for prolonged periods. From equation (2) and (3) one obtains $[T_1 - T_2]$

$$[T_1-T_2]=-[1/(H_1+h_1)][(T_f-T_{absorber})h_2+(T_r-T_f)H_1+(T_t-T_f)h_1] \ (6)$$

Keeping temperatures and the height h_1 and h_2 constant but varying the height H_1, one can write

$$d[(T_1-T_2)/dH_1]=[-\{(T_f-T_{absorber})\ h_2 /(H_1+h_1)^2\}-\{(T_t-T_f)h_1/ (H_1+h_1)^2\}-\{(T_f-T_r)/ (H_1+h_1)\}+ \{[\{(T_f-T_r)/ (H_1+h_1)\}][H_1 /(H_1+h_1)]\} \qquad (7)$$

Under night time conditions, and with the tank full of hot water, it is reasonable to expect that T_f is greater than T_a, T_t is greater than T_f and T_f is greater than Tr. With the result that RHS of equation (6) is (-ve) and the temperature difference $(T_1 - T_2)$ decreases with increasing H_1. If H_1 is greater than h_1 then one would find $T_2=\{T_f-(T_f-T_{absorber})[h_2 /H_1]\}$

For the limit $T_1=T_r$. Thus by raising the height of the storage tank relative to the top of absorber, the temperature difference causing the reverse flow is decreased [4]. By careful design fabricated by a reputed solar industry and measurements were and installation, the reverse flow can be completely avoided. For reverse flow to be completely absent, the tank should be placed as high as possible above the collector (i.e. 200mm) between 150 mm to 250 mm depending upon collector fluid flow geometry. However, one has to consider the extra piping associated with the cost and also thermal losses. Some novel designs of solar water heating systems which can completely eliminate reverse flow and also allow the placement of hot water storage tank at an acceptable level are described [5].

4.2 Modified system design for free convection solar water heating systems

In natural convection solar water heating systems, buoyant forces created by density gradients in the fluid inside the collector create pressure, which causes the liquid to flow in the collector loop. These systems don't need a pump, and the tank is typically positioned above the collector. Reverse flow is a frequent issue in these systems, which causes significant heat losses during the off sun shining hours.

In thermosyphonic free convection solar water heating systems, the phenomenon of reverse flow causes significant heat losses from solar energy collectors during the hours when the sun is not shining. Only a tiny amount of literature has addressed in the literature consequently [6].

Reverse flow can occur in the thermosyphonic solar water heating systems during periods of no sunshine hours, especially when the bottom of storage tank is placed below the top of the solar collector. During the day time, the water in the storage tank gets heated and the top portion remains hot as compared to bottom portion due to radiation falling on a solar collector which absorb solar radiation to heat water in the solar collector. From the storage tank, during off sunshine hours the hot water comes in to solar collector due to density difference and gets cooled much faster than the pipe due to large surface area of the collector is exposed to sky. The results is that the left hand side of the tube gets cooler and becomes havier while right hand side of the tube remains hot and flow of liquid starts in the reverse direction. This brings down the temperature of water in the storage tank drastically. Measurements and discussion of reverse flow is rare in literature. Recently few investigators have observed the phenomenon of reverse flow in the system and carried out experimental studies on pressurized and non-pressurized systems and found that if the tank is kept very high above the collector, then there is always some flow of liquid through the collector especially during night time, if the outlet of collector is connected near the middle of the tank. This also results in considerable losses resulting poor thermal performance of the system [6].

5. Results and Discussion

The performance of modified thermosyphonic solar water heating systems have been presented in which reverse flow has been completely eliminated. These systems were performed on pressurized and non-pressurized system and sound theory for preventing reverse flow in natural convection solar water heating systems was established. The derivation of thermosyphonic pressurized and non-pressurized systems have been developed and numerical computation for water temperature and thermal efficiency were performed [7]. The results of these computation and validated with experimental measurements were compared for these systems are shown in Table 1 and Table 2 respectively.

Table 1: Thermal performances of single pass thermosyphonic non pressurized solar water heating system using parallel tube fluid flow channel absorber (Collector Area =2.1m^{2})

Time (hr)	Inlet Water Temperature (^{o}C)	Ambient Temperature (^{o}C)	Solar Intensity (W/m^{2})	Collector Outlet fluid temperature Exp. (T$_{CO}$) (^{o}C)	Collector Outlet fluid temperature Model (T$_{CO}$) (^{o}C)	Collector mass flow rate Exp. (Kg/hr)	Collector mass flow rate (Model) (Kg/hr)	Collector temperature difference (^{o}C) Exp.	Collector temperature difference (^{o}C) Model
9AM	21.0	21.7	430.0	66.6	65.5	3.0	2.96	45.0	44.5
10	24.0	23.5	535.0	78.0	79.8	9.0	8.97	54.0	55.8
11	28.0	26.0	675.0	83.0	84.2	11.0	11.0	55.0	56.2
12	32.0	28.4	760.0	84.0	84.8	14.0	14.05	52.0	52.8
13PM	32.5	29.3	765.0	83.0	84.5	12.0	13.55	50.5	52.0
14	34.5	29.7	695.0	81.5	80.8	11.55	12.0	47.0	46.3
15	35.5	29.8	560.5	77.0	75.9	7.0	7.25	41.5	40.5
16	35.0	29.9	387.0	65.0	66.1	6.0	5.96	30.5	31.1
17	33.5	28.8	182.0	41.0	40.5	3.55	2.97	5.5	7.0

The experimental and theoretical results show a strong correlation, indicating the reliability of the findings. For non-pressurized solar hot water systems equipped with parallel tube absorbers, the average thermal efficiency was found to be 41% in single-pass mode and 27.3% in multi-pass mode. These results highlight the performance of non-pressurized systems, which experience relatively lower heat losses due to the absence of pressurization, allowing for higher efficiencies. In contrast, pressurized solar hot water systems, which operate at higher absorber temperatures, tend to exhibit increased heat losses, leading to lower system efficiency. Specifically, for pressurized systems with meander tube absorbers, the efficiency was determined to be 30% in single-pass mode, and 25.4% for systems using serpentine fluid flow channel absorbers. These variations in efficiency can be attributed to the design and thermal dynamics of the pressurized systems, where higher temperatures increase the potential for heat dissipation. Overall, the comparison between these systems provides valuable insights into the performance differences based on design and operational modes, with non-pressurized systems demonstrating higher efficiency due to lower thermal losses.

Table 2: Thermal performances of single pass thermosyphonic non pressurized solar water heating system using meander fluid flow channel absorber (Collector Area =2.1m^{2})

Time (hr)	Inlet Water Temperature (^{o}C)	Ambient Temperature (^{o}C)	Solar Intensity (W/m^{2})	Collector Outlet fluid temperature Exp. (T$_{CO}$) (^{o}C)	Collector Outlet fluid temperature Model (T$_{CO}$) (^{o}C)	Collector mass flow rate Kg/hr) Exp	Collector mass flow rate (Kg/hr) (Model)	Collector temperature difference (^{o}C) Exp.	Collector temperature difference (^{o}C) Model
9AM	21.0	21.7	430.0	65	61	0	0.2	44.0	40.0
10	24.0	23.5	535.0	78	81	3.70	4.0	54.0	57.0
11	28.0	26.0	675.0	41.5	89.9	6.57	6.6	63.5	61.9
12	32.0	28.4	760.0	96.0	98.9	10.0	10.5	64.0	66.9
13PM	32.5	29.3	765.0	87.5	96.8	9.6	10.1	55.0	64.3
14	34.5	29.7	695.0	91.5	94.8	5.6	6.2	57.0	60.3
15	35.5	29.8	560.5	90.0	92.5	4.6	5.15	54.5	59.3
16	35.0	29.9	387.0	82.5	88.2	2.3	2.35	47.5	53.2
17	33.5	28.8	182.0	57.5	54.7	0	0.3	24.0	25.2

In the multipass mode, the system efficiency of meander tube absorbers is 20%. The thermal performance parameters for eight pressurized and eight non-pressurized solar hot water systems, each utilizing parallel tube absorbers, are shown in Table 3. These parameters were determined using the HWB equation, which provides a method for evaluating the thermal efficiency and performance characteristics of solar hot water systems. The comparison of pressurized and non-pressurized systems highlights differences in their performance, offering insights into how system design and operational modes influence thermal efficiency and overall effectiveness in various applications.

Table 3: Performance Parameters of thermosyphonic free convection solar hot water systems (collector Area=2.1 m^2)

S.No	Pressurized thermosyphonic systems using serpentine fluid flow channel (10 turns) of copper tube length (16.6 meters)	Non-Pressurized thermo-syphonic systems using parallel tube fluid flow channels (10 tubes) of copper tube length
1	F'(τα)e=0.725 and F'U_L =13.56	F'(τα)e=0.720 and F'U_L =6.344
2	F'(τα)e=0.730 and F'U_L =11.23	F'(τα)e=0.725 and F'U_L =6.12
3	F'(τα)e=0.725 and F'U_L =13.82	F'(τα)e=0.720 and F'U_L =6.344
4	F'(τα)e=0.720 and F'U_L =14.40	F'(τα)e=0.725 and F'U_L =8.089
5	F'(τα)e=0.725 and F'U_L =12.083	F'(τα)e=0.725 and F'U_L =6.12
6	F'(τα)e=0.720 and F'U_L =15.158	F'(τα)e=0.720 and F'U_L =6.344
7	F'(τα)e=0.720 and F'U_L =18.40	F'(τα)e=0.725 and F'U_L =8.089
8	F'(τα)e=0.720 and F'U_L =11.25	F'(τα)e=0.725 and F'U_L =6.12

6. Conclusions and Recommendations

- A single-pass thermosyphonic solar water heating system using a meander tube fluid flow channel is recommended for water purification in rural, remote areas with poor water quality, particularly for drinking purposes.
- Single-pass pressurized solar hot water systems, which eliminate reverse flow, have two unique characteristics: they provide water at a consistent temperature regardless of insolation levels and allow the main water storage tank to be placed anywhere, even below the solar collector.
- The experimental results closely aligned with the computed results derived from the equations for both pressurized and non-pressurized solar hot water systems.
- Non-pressurized solar hot water thermosyphonic systems with parallel tube absorbers, using aluminum finned absorbers, exhibit an average thermal efficiency of 41% in single-pass mode and 27.3% in multi-pass mode.
- The system efficiency for meander tube absorbers is 30% in single-pass mode and 20% in multi-pass mode due to higher absorber temperatures and increased heat losses in pressurized solar hot water systems.
- To reduce top heat losses from solar flat plate collectors, honeycomb structures have been proposed, which can reduce approximately 70% of top heat losses.

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