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Research Article

Design, Fabrication, and Efficiency Study of a Novel Solar Thermal Water Heating System: Towards Sustainable Development

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This paper investigated a novel loop-heat-pipe based solar thermal heat-pump system for small scale hot water production for household purposes. The effective use of solar energy is hindered by the intermittent nature of its availability, limiting its use and effectiveness in domestic and industrial applications especially in water heating. The easiest and the most used method is the conversion of solar energy into thermal energy. We developed a prototype solar water heating system for experimental test. We reported the investigation of solar thermal conversion efficiency in different seasons which is 29.24% in summer, 14.75% in winter, and 15.53% in rainy season. This paper also discusses the DC heater for backup system and the current by using thermoelectric generator which are 3.20 V in summer, 2.120 V in winter, and 1.843 V in rainy season. This solar water heating system is mostly suited for its ease of operation and simple maintenance. It is expected that such novel solar thermal technology would further contribute to the development of the renewable energy (solar) driven heating/hot water service and therefore lead to significant environmental benefits.

1. Introduction

Water heating for domestic purposes is a simple and effective way of utilizing solar energy. The initial cost of solar water heating system is very high without any operating cost. It is a natural solar thermal technology. In this system, incident solar radiation is converted into heat and transmitted to a transfer medium such as water [1]. The solar energy is the most capable of the alternative energy sources. Due to increasing demand for energy and rising cost of fossil fuels (i.e., gas or oil), solar energy is considered as an attractive source of renewable energy. Solar heater is a device that uses solar energy to produce steam for domestic and industrial applications [2–5]. Heating of water consumes nearly 20% of total energy consumption for an average family. Solar water heating systems are the cheapest and most easily affordable clean energy available to homeowners that may provide hot water required for a family. Solar water heaters can operate in any climate [6–9]. The performance of these heaters varies depending on the availability of solar energy at that locality and more importantly on the temperature of cold water coming into the system. It can be either active or passive [10]. A thermosiphon solar water heater relies on warm water rising, a phenomenon known as natural convection, to circulate water through the solar collector and to the storage water tank. The thermosiphon effect for solar water heating system has been employed with solar collectors as the principal heating component. These solar heating systems use either direct heating or indirect heating by the collector [11–13]. In these cases, the thermosiphon induced flow is a result of the incident solar radiation, but it is also affected by the hot water removal pattern. Recently, a fuzzy model system is used to predict the outlet water temperature of a thermosiphon solar water heating system [14]. Presently, solar and other alternative energy resources are being harnessed for various applications such as power generation, air conditioning,

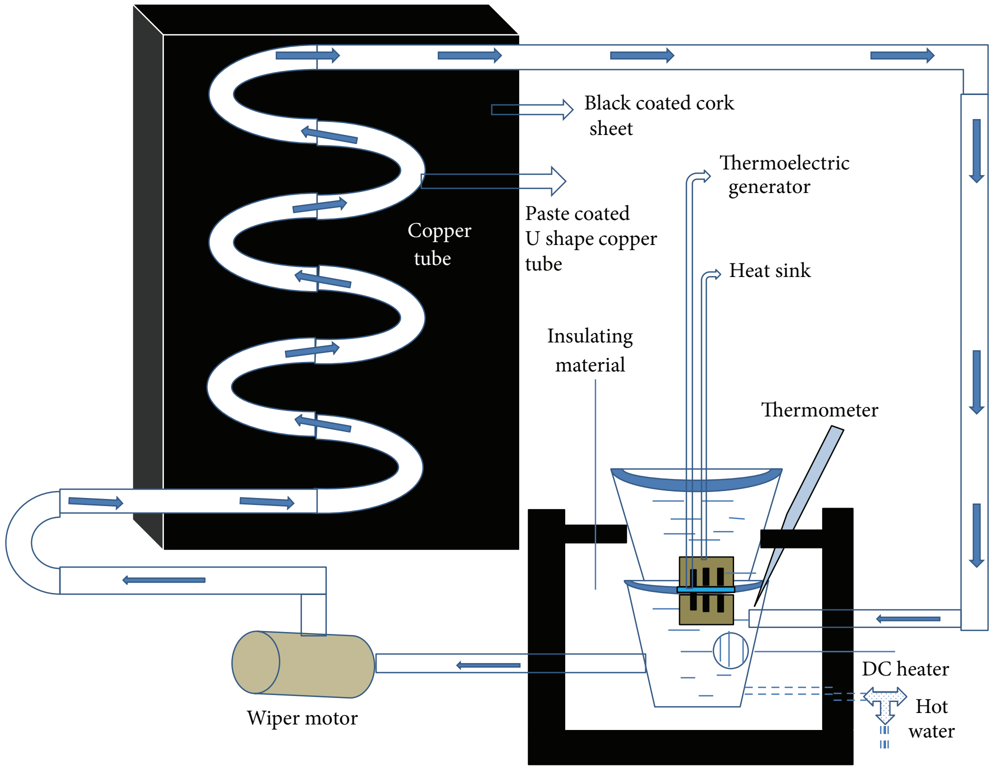

Figure 1: A proposed model of solar water heating system.

space heating, and domestic hot water system. Photovoltaic thermal technology (PVT) refers to the solar thermal collectors that use PV cells as an integral part of the absorber plate. This kind of system generates both thermal and electrical energy simultaneously [15]. The solar water heaters in various Indian stations were reported to provide 100 L of hot water at an average temperature of 50–70°C, which can be retained to 40–60°C until used next day morning [16]. The spiral flow absorber collector at temperature of 55°C achieved the best mass flow rate at 0.011 kg/sec and generated combined PVT efficiency of 64%, with 11% of electrical efficiency and maximum power of 25.35 W. On the other hand, a single pass rectangular collector absorber obtained the best mass flow rate of 0.075 kg/sec, when the surface temperature was 392°C, generating combined PVT efficiency of 55%, with 10% of electrical efficiency and maximum power of 22.45 W [15]. Al_2O_3 and MWCNT water nanofluids have significant effect on the efficiency of FPSC (flat plate solar collector) experimentally. The results showed that using Al_2O_3 and MWCNT water nanofluids in comparison with water as working fluid increased the efficiency up to 28.3% and 35%, respectively [17]. The performance of a new hybrid domestic hot water system that combines with a thermoelectric air conditioner (TEC1-12704) indicated that this system can heat up 120 liters of water to 50°C within 2 hours and the corresponding highest coefficient of performance of hybrid system is 3.12% [18]. It has been found that, in summer, the solar heater heats the water to 52°C. In winter, the temperature of cold water in the tank of the house is around 16°C to 18°C against 22°C to 25°C in summer. Due to the temperature difference between the seasons and the reduction of solar radiation in winter, the thermal efficiency drops from 52°C in summer to a maximum of 38°C in winter [19].

2. Materials and Methodology

2.1. Materials and System Design. The heat management and storage system consists of pipe network, storage vessel, and backup system. The design of the system consisted of a reservoir, wiper motor, DC battery, copper tube, insulating materials, coating materials, casing, glazing materials, and seals, as well as different piping systems. Figure 1 presents a complete proposed model of solar water heating systems. Copper tube was selected for the system because of its high thermal conductivity and anticorrosive properties. Black paint and carbon powder were used for their high absorptivity and glass was used as glazing material for its high transmissivity.

2.2. Experimental Setup and Process Description. This study involves the feasibility comparison of solar water heater systems. For the purpose of this research, solar hot water system was designed for a family of four members. The instrumental setup of the heating system is illustrated in Figure 2. When switching on the motor, water from the reservoir first comes to the U shape copper tube of diameter 3/8 inches and thermal conductivity 376 Wm/K. The casing is covered with a black coated cork sheet whose acoustic

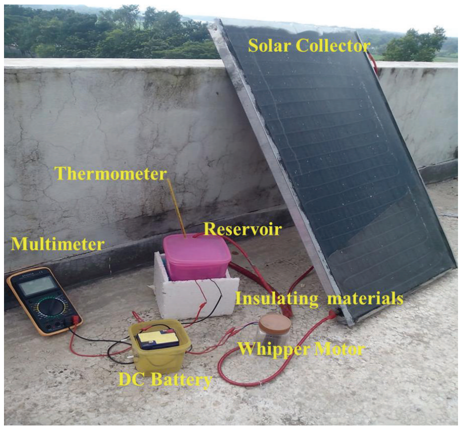

Figure 2: An instrumental setup of solar water heating system.

resistivity is 1.2×10^5. The casing front surface is closed with a low iron glass (approximately 0.85–0.90 at normal incidence). The casing is kept in a hot, shiny place where the copper tube gets greater amount of heat. The hot water which is coming from the copper tube goes to the reservoir through another insulating pipe and this hot water is again recirculating several times through the copper tube in the similar manner. For backup support or for rapid heating process, a heating coil driven by DC battery of 6 V is used in the reservoir. Then, two heat sinks (one contains water of normal room temperature and another of hot temperature) result in a temperature difference according to Peltier effect and hence produce electricity.

3. Results and Discussion

3.1. Factors Affecting the Temperature of Hot Water

3.1.1. Effect of Exposure Time to Sunlight. The performances of solar collectors are largely affected by their operating temperature which depends on exposure time to sunlight. The temperature and intensity of sunlight vary according to the seasons. In the summer season, the weather is hotter and shiny compared to rainy and winter season that results in high temperature as recorded to be approximately 77.5°C as illustrated in Figure 3. On the other hand, in rainy season, the recorded temperature is the lowest among the seasons because of the excessive rain and violent blasts of wind blowing. Besides, the temperature varies throughout the day in case of all the seasons. The maximum temperature of water is found in the duration between 10.00 am and 1.00 pm due to the hot, shiny, and acute warmness of weather for higher intensity of solar energy. The intensity of solar energy in morning remains low and starts to fall down from the highest temperature in afternoon.

3.1.2. Effect of DC Heater. Figure 4 shows the temperature profile of the heating system using DC heater. In this case, a DC heater that consumes the minimum amount of electricity from a 6 V rechargeable battery is used for backup system. In the duration between 8.00 and 10.00 am, in summer season,

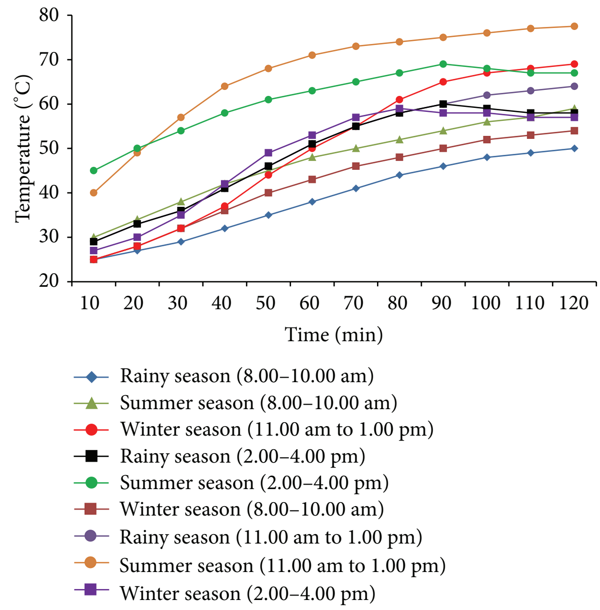

Figure 3: Response of outlet hot water temperatures in different seasons.

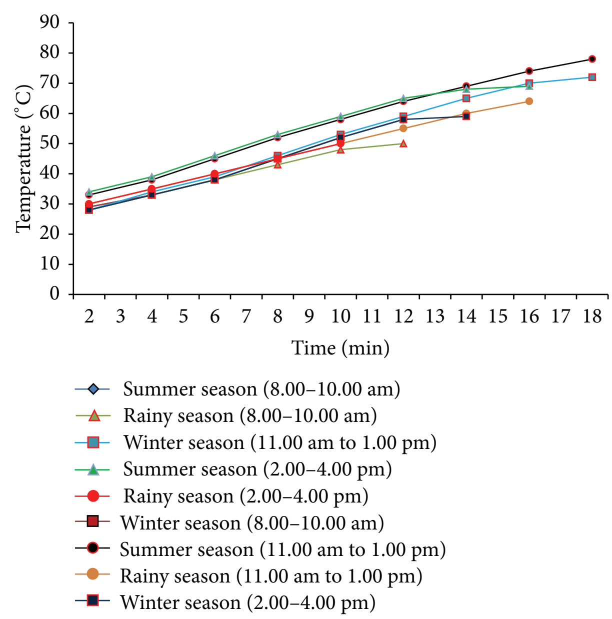

Figure 4: Comparison of temperature profile by using DC heater.

the water temperature is raised to 58°C at 12 minutes of heating, whereas, in winter season, the temperature is raised to 52°C at 10 minutes of heating and in rainy season the temperature is raised to 50°C at 11 minutes of heating. The highest temperature (78°C) among the seasons is recorded in the summer season in the duration between 11.00 am and 1.00 pm at heating time of 18 minutes. In addition to this, the highest temperature in winter season and rainy season is recorded to be about 72°C and 64°C at heating time of 17 minutes and 16 minutes, respectively.

Table 1: Thermoelectric data of different seasons.

Time (min)	Summer RT 25°C, WT 24°C				Winter RT 25°C, WT 22°C				Rainy RT 25°C, WT 24°C			
	dT °C	*V* (V)	*R* (mΩ)	*C* (mA)	*dT* °C	*V* (V)	*R* (mΩ)	*C* (mA)	*dT* °C	*V* (V)	*R* (mΩ)	*C* (mA)
8.00–8.10	6	0.200	0.769	183	3	0.127	1.04	122	1	0.080	1.02	078
8.10–8.20	10	0.420	1.1	381	6	0.224	1.09	205	3	0.127	1.04	122
8.20–8.30	14	0.500	1.2	416	10	0.439	1.2	365	5	0.325	1.1	295
8.30–8.40	18	0.740	1.3	528	13	0.679	1.3	522	8	0.420	1.2	350
8.40–8.50	20	0.937	1.4	669	17	0.821	1.4	586	10	0.521	1.2	434
8.50–9.00	23	1.110	1.6	693	20	0.925	1.5	616	13	0.590	1.2	491
9.00–9.10	25	1.320	1.8	859	22	1.110	1.6	693	15	0.679	1.3	522
9.10–9.20	26	1.547	2.0	773	24	1.226	1.7	721	16	0.720	1.3	553
9.20–9.30	28	1.663	2.2	755	25	1.373	1.8	762	18	0.842	1.4	601
9.30–9.40	30	1.880	2.5	752	27	1.492	1.9	785	20	0.937	1.5	624
9.40–9.50	30	1.990	3.0	663	28	1.590	2.0	795	23	1.110	1.6	693
9.50–10.00	31	2.020	3.1	651	28	1.755	2.3	763	24	1.320	1.8	733
11.00–11.10	11	0.220	1.09	201	1	0.090	1.05	085	2	0.127	1.04	122
11.10–11.20	20	0.337	1.1	306	4	0.210	1.09	192	6	0.310	1.1	281
11.20–11.30	28	0.520	1.2	433	8	0.429	1.2	357	9	0.420	1.2	350
11.30–11.40	34	0.720	1.3	567	13	0.642	1.3	493	13	0.590	1.2	491
11.40–11.50	38	0.921	1.4	657	20	0.829	1.4	592	18	0.842	1.4	601
11.50–12.00	41	1.110	1.6	693	25	1.010	1.6	631	23	1.110	1.6	693
12.00–12.10	43	1.470	1.9	773	30	1.235	1.7	726	26	1.213	1.7	713
12.10–12.20	43	1.770	2.3	769	35	1.479	1.9	747	30	1.327	1.8	737
12.20–12.30	44	2.013	2.9	694	38	1.621	2.1	771	31	1.422	1.9	748
12.30–12.40	45	2.450	3.1	790	40	1.877	2.5	750	33	1.566	2.0	783
12.40–12.50	46	2.920	3.2	912	41	1.972	2.8	704	34	1.724	2.3	749
12.50–1.00	46.5	3.20	3.4	947	42	2.120	3.0	706	35	1.843	2.5	737
2.00–2.10	19	0.240	1.09	220	4	0.122	1.05	116	1	0.089	1.02	087
2.10–2.20	24	0.462	1.1	420	7	0.229	1.09	210	4	0.224	1.09	205
2.20–2.30	27	0.532	1.2	443	12	0.333	1.1	302	8	0.420	1.2	350
2.30–2.40	31	0.649	1.3	499	18	0.527	1.2	439	11	0.520	1.2	433
2.40–2.50	34	0.842	1.4	601	25	0.726	1.3	558	15	0.649	1.3	499
2.50–3.00	35	1.010	1.6	631	28	0.952	1.4	680	18	0.842	1.4	601
3.00–3.10	37	1.220	1.7	717	32	1.057	1.5	704	19	0.937	1.5	624
3.10–3.20	39	1.447	1.9	761	33	1.267	1.7	745	21	1.112	1.6	695
3.20–3.30	41	1.552	2.0	776	34	1.387	1.8	770	23	1.213	1.7	713
3.30–3.40	40	1.449	1.9	762	34	1.306	1.8	725	22	1.190	1.8	730
3.40–3.50	40	1.402	1.9	737	33	1.221	1.7	718	21	1.02	1.9	756
3.50–4.00	39	1.363	1.9	717	32	1.123	1.7	660	20	0.950	2.0	751

3.1.3. Effect of Carbon Powder. The carbon powder is used as coating layer in solar water heater due to its low cost and nontoxicity. The temperature raise of the system is directly proportional to the percentage of carbon in the coating layer. The maximum achieved outlet water temperature is about 80°C in June and 69°C in February.

3.2. Thermoelectric Analysis of the Heater. A thermoelectric device converts the temperature difference across the device to electric voltage according to the thermoelectric principle. This thermoelectric effect is used to generate electricity. Table 1 shows the thermoelectric reading at different time in different season.

3.2.1. Voltage and Temperature Profile. The efficiency of a thermoelectric device depends on the temperature difference across the device. The Peltier effect is based on the temperature difference and therefore when the temperature difference is higher, the amount of electricity production is greater. In the duration of 8.00 to 10.00 am, the temperature difference is higher in summer season than the winter and rainy season due to higher intensity of solar energy, which provides greater

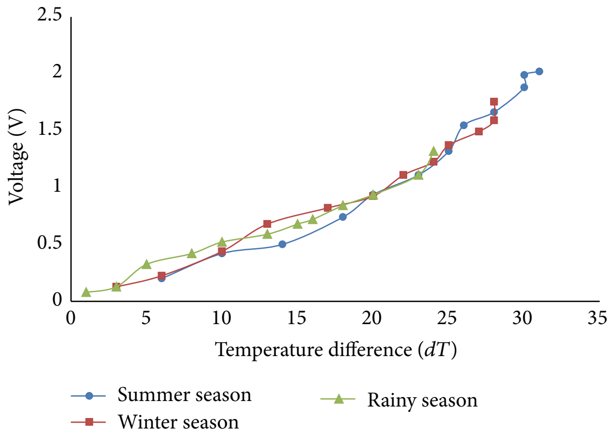

Figure 5: Comparison of temperature difference versus voltage in the duration of 8.00–10.00 am by using thermoelectric generator.

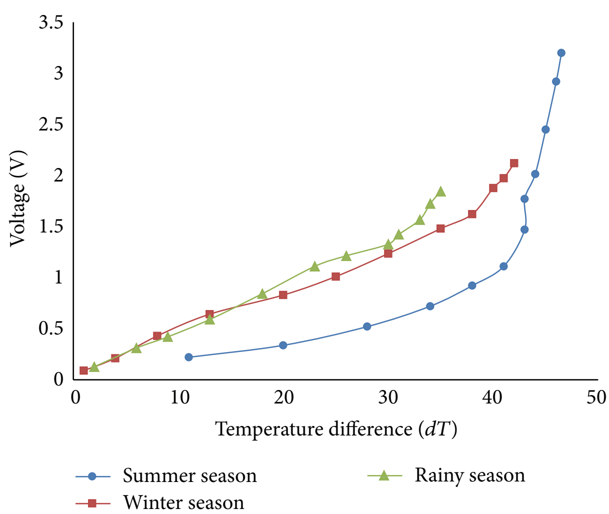

Figure 6: Comparison of temperature difference versus voltage in the duration of 11.00 am to 1.00 pm by using thermoelectric generator.

amount of voltage. Figure 5 shows that, in summer season in the duration of 8.00 to 10.00 am, about 2.02 V of electricity is produced due to higher temperature difference, whereas in winter and in rainy season about 1.755 V and 1.32 V of electricity are produced, respectively.

In the duration of 11.00 am to 1.00 pm in summer season, the solar collector takes the maximum heat from solar energy and gains the higher hot water temperature. Figure 6 shows that the maximum voltage is 3.20 V when the temperature difference is 46.5°C in summer season. In winter season, the voltage is 2.12 V when the temperature difference is 42°C and, in rainy season, the voltage is 1.843 V when the temperature difference is 35°C in the duration of 11.00 am to 1.00 pm.

In the duration of 2.00–4.00 pm in summer season, the solar collector takes the maximum heat from solar energy than the winter and rainy season. It is found that the temperature difference gradually decreases in the duration of 3.25–4.00 pm because of the lower intensity of solar energy.

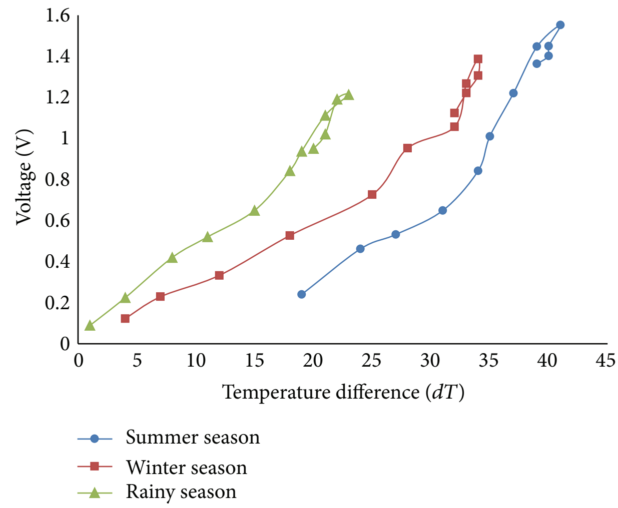

Figure 7: A comparison of temperature difference versus voltage in the duration of 2.00–4.00 pm by using thermoelectric generator.

Figure 7 shows that the maximum voltage is 1.40 V when the temperature difference is 40°C in summer season. In winter season, the voltage is 1.22 V when the temperature difference is 33°C and, in rainy season, the voltage is 1.02 V when the temperature difference is 21°C.

3.2.2. Current and Voltage Profile. According to Ohm's law, the current increases gradually with the increase of voltage. But, from a certain point of increasing the voltage, the current decreases gradually, because, after reaching a point of voltage, some portions of voltage are used to run the DC battery. During summer season, at 8:00 to 10:00 am, when voltage reaches 1320 mV, the highest amount of current, about 859 mA, is obtained. However, when the voltage becomes 1547 mV, the current falls down at 773 mA and it gradually decreases to 651 mA as presented in Figure 8. On the other hand, during winter season, when the voltage reaches 1590 mV, the highest amount of current is about 795 mA and then falls down to be 763 mA. However, at rainy season, the highest amount of current, 733 mA, is obtained at a voltage of 1320 mV.

During summer season, at 11:00 am to 1:00 pm when voltage reaches 1470 mV, the current, about 773 mA, is obtained. On the other hand, when voltage becomes 1770 mV, the current falls down to be at 769 mA and it gradually decreases to 694 mA as presented in Figure 9. But, after recharging the battery, the current rises to 794 mA and gradually increases to 947 mA. During winter season, the highest amount of current, about 771 mA, is recorded at a voltage of 1621 mV and gradually decreases to 706 mA from its peak value. But, at rainy season, the highest amount of current 783 mA is estimated at a voltage of 1566 mV.

During summer season (at 2:00–4:00 pm) when voltage reaches 1552 mV, the highest current is about 776 mA and when voltage becomes 1449 mV, the current falls down at 762 mA as illustrated in Figure 10. During winter season, when voltage reaches 1387 mV, the highest amount of current about 770 mA falls down to 725 mA at 1306 mV. However,

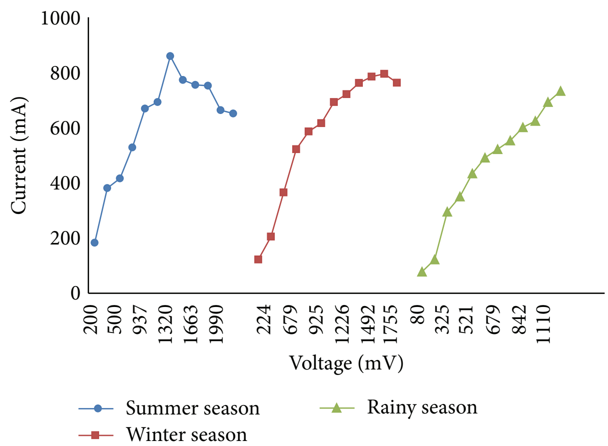

FIGURE 8: Comparison of voltage versus current in the duration of 8.00–10.00 am in summer, winter, and rainy season.

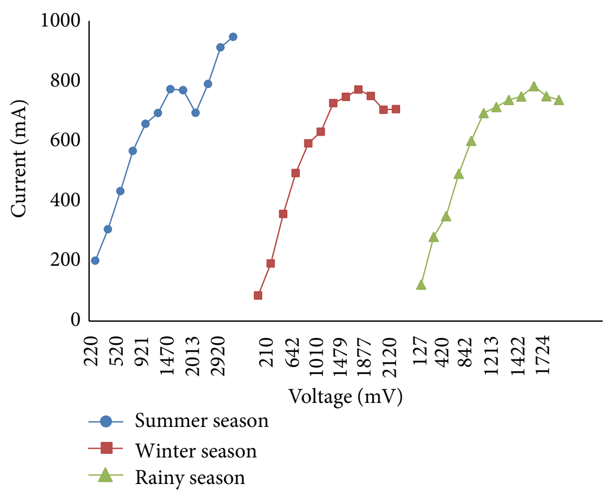

FIGURE 9: Comparison of voltage versus current in the duration of 11.00 am to 1.00 pm in summer, winter, and rainy season.

in rainy season, the highest amount of current 756 mA is obtained at a voltage of 1437 mV.

3.2.3. Voltage and Resistance Profile. The voltage developed in an electric system is largely dependent on resistance as well as the speed and the density of the electrons. Figure 11 shows the relationship between voltage and resistance. In the duration of 8.00–10.00 am in summer season, the resistance is 3.1 mΩ with the corresponding voltage of 2020 mV, whereas in winter season the resistance is 2.3 mΩ with the corresponding voltage of 1755 mV. Similarly in rainy season, this value is 1.8 mΩ with the corresponding voltage of 1320 mV.

In the duration of 11.00 am to 1.00 pm in summer season, 3.4 mΩ resistance is estimated at a voltage of 3200 mV and in winter season 3.0 mΩ is obtained at a voltage of 2120 mV as shown in Figure 12. Similarly, in rainy season, 2.5 mΩ is recorded at a voltage of 1843 mV.

In the duration of 2.00–4.00 pm in summer season, the resistance is recorded to be about 1.9 mΩ at a voltage of

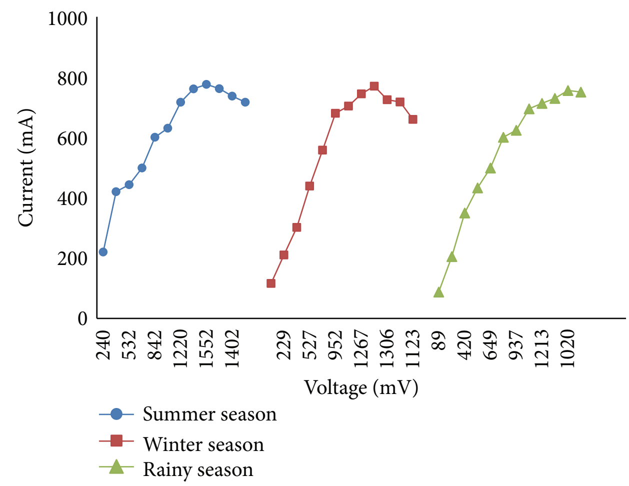

FIGURE 10: Comparison of voltage versus current in the duration of 2.00–4.00 pm in summer, winter, and rainy season.

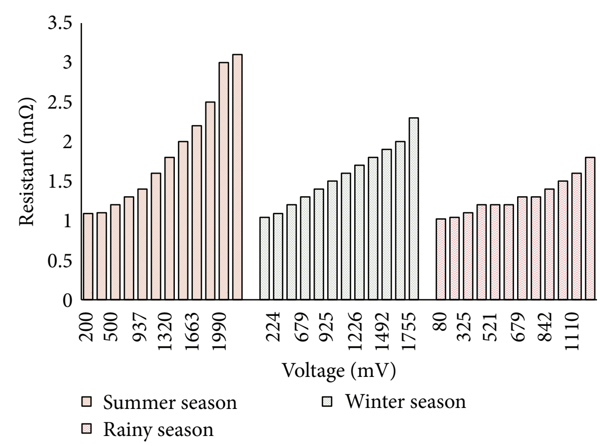

FIGURE 11: Comparison of voltage versus resistance in the duration of 8.00–10.00 am in summer, winter, and rainy season.

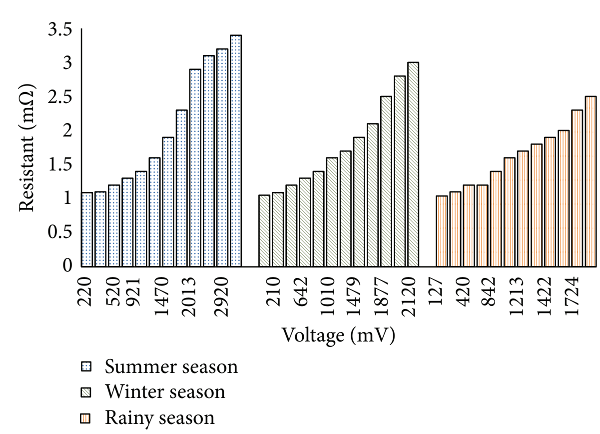

FIGURE 12: Comparison of voltage versus resistance in the duration of 11.00 am to 1.00 pm in summer, winter, and rainy season.

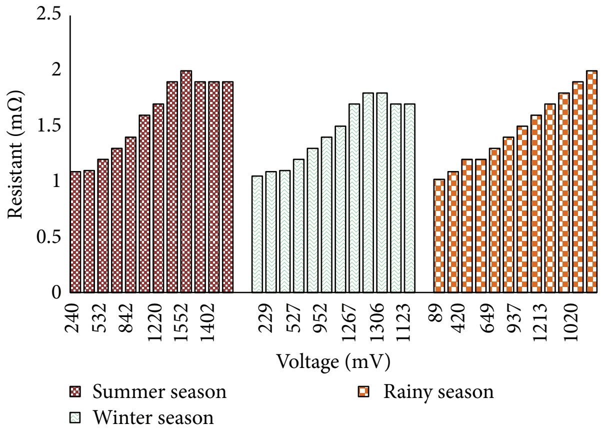

Figure 13: Comparison of voltage versus resistance in the duration of 2.00–4.00 pm in summer, winter, and rainy season.

1363 mV and in winter season this value is about 1.7 mΩ at a voltage of 1123 mV as presented in Figure 13. On the other hand, in rainy season, 2.0 mΩ resistance is recorded which is corresponding to the voltage of 950 mV.

3.3. Power and Efficiency Analysis. Efficiency of solar water heating system is given by the ratio of energy released from the solar water heating system to energy gained by the system. Considering the mass of water 0.50 kg and the specific heat of water 4.186 kJ/kg°C, the efficiency (η) for each season is calculated at the highest temperature duration of 11.00 am to 1.00 pm.

Energy input or energy gained by solar water heating system is estimated by the following equation:

$$E_{\text{in}} = mC_p dT, \quad (1)$$

where m is the mass of water in kg; C_p is the specific heat of water in kJ/kg°C; and dT is the temperature difference between final temperature of water and initial temperature of water.

On the other hand, energy released by solar water heating system or output of energy is calculated by the following equation:

$$E_{\text{out}} = Pt = VIt, \quad (2)$$

where P is the power in watt; V is the voltage in volt; I is the current in ampere; and t is the time in seconds.

The efficiency of the solar water heating system in summer is about 29.24% with power of 4.1216 W as depicted in Table 2. On the contrary, the efficiency of the system in winter and rainy season is 14.75% and 15.53%, respectively.

3.4. Cost Analysis of the System. Actually, the cost analysis of this solar heating system depends on the number of family members, quantity of hot water required, and also the cost of heating sources. A comparative cost analysis is made among different energy usages systems for a family consisting of four members. It is assumed that the family requires about 50 liters of water per day including 16 liters for shower, 12 liters for clothes washing, and 10 liters for faucet. Accordingly, the family requires approximately 1500 liters of hot water per month and 18250 liters of hot water per year.

Table 2: Power and efficiency of the system at different seasons.

Season	dT	V	I	P	η
Summer	48.5	3.20	1.288	4.1216	29.24
Winter	45	2.10	0.921	1.93	14.75
Rainy	35	1.82	0.868	1.58	15.53

Table 3: Cost estimation of the proposed solar water heating model.

Component	Amount (BDT)
Copper tube	2000
Black paint	80
Carbon powder	40
Cork sheet	40
Araldite glue	250
Silver sheet	300
Low iron glass	300
Wiper motor	300
Heating coil	120
DC battery (6 V)	600
Plastic box	120
Cotton	10
Wire	10
Pipe	30
Others	300
Total amount = BDT 4500	

In case of solar heating system, the input energy is the renewable solar energy. Therefore, the cost of the system is only the manufacturing cost without any running cost for a lifetime of five years. The construction cost of the proposed system is shown in Table 3.

If electricity is used for the heating of water instead of solar heating system, then about 10 kWh of electricity is required to heat 50 liters of water. Accordingly, the total cost of heating water for the family is about BDT 19162.5 per year and BDT 95812.5 for five years. Therefore, the use of solar heating system reduces the energy consumption cost of the family by 95.30% for a lifetime of five years of the system. On the other hand, the cost of gas to heat the same amount of water is approximately BDT 65 per day. Therefore, the total heating cost for five years duration is about BDT 118625 which is almost 96.21% higher than the cost of proposed solar heating system. With the base case of gas geyser, to fulfill the hot water requirements during winter, summer, and rainy season, the system is 60% efficient.

4. Conclusion and Recommendation

The purpose of this work was to develop a low cost solar water heating system. We get the highest temperature, 77.5°C, of water and 3.20 V by using this device. We also use DC heater for backup system and 18 minutes is required to raise the temperature up to 77.5°C and higher temperature is also obtained by this instrument. The scarcity of electricity and gases in our country is too high. Due to limited natural resources, the cost of gases and electricity is increasing rapidly. As a result, it would not be possible to use hot water for all types of domestic work by using gas or electricity. So, we have tried to invent this type of solar water heater so that it can meet all types of demand when hot water is needed without using gas or electricity.

Future recommendation will focus on future testing and exploration of financing options. Additional testing is needed to evaluate insulation options and assess the performance of other low cost materials and future work will involve modifying this design to meet the needs and materials of other regions.

Nomenclature

RT: Room temperature (°C)
WT: Water temperature (°C)
dT: Temperature difference (°C)
V: Voltage
R: Resistance (Ω)
I or C: Current (A).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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