Development and performance evaluation of indigenized flat plate collector water heater for domestic and industrial applications

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Abstract: Pakistan is facing severe energy crises from the last decade resulting daily electric blackouts from 8 to 12 h. The limited fossil fuel reserves and its environmental consequences have led to boost research and development of alternate energy resources. A huge amount of fossil fuels and electricity is being consumed for the generation of low to medium temperature heat energy for domestic, residential, agro-industrial and processing units. This low to medium temperature heat energy required can easily be fulfilled using solar collectors. This paper focus on the development of a flat plate collector using local infrastructure to reduce its initial cost. The collector consists of a window glass, absorber plate coated with black matt paint, copper tubes, inlet and outlet pipes, rockwool insulation and a wooden frame. The results showed that the average efficiency of the solar collector was found to be 47.06%. The complete collector unit has been developed using indigenous resources to reduce its initial cost without compromising on its efficiency. Due to ideal climatic conditions of Pakistan for solar thermal energy, this system can be used for domestic, residential, and agro-industrial applications especially in rural and remote areas having no access to natural gas or electricity.

Keywords: renewable energy; flat plate collector; collector efficiency; payback time

Citation: Nauman, M. H., A. Ghafoor, A. Munir, and M. Ahmad. 2015. Development and performance evaluation of indigenized flat plate collector water heater for domestic and industrial applications. AgricEngInt: CIGR Journal, 17(4): 156-164.

1 Introduction

Pakistan is developing country of Asia. It is unfortunate that the country is facing severe energy crises from the last decade resulting daily electricity blackouts from 8 to 12 h a day (Ghafoor and Munir, 2015). This situation has drastically affected the agricultural, commercial and industrial sector of the country. According to a report, the installed capacity of Pakistan for power generation is about 22800 MW. The existing energy gap between supply and demand is produced because power generation share with oil and gas (non-renewable) is about 64.2% and from hydel (renewable) it is about 29.9% while remaining comes from wind, solar, nuclear and biomass (Pakistan Energy Year Book, 2012).The world in 21st century requires more energy to meet its growing energy demand. Present energy sources includes fossil fuel, coal, natural gas, nuclear, firewood etc. In 1970s, it was revealed that these limited resources are depleting rapidly. In the intimidation of this prediction and to save these limited resources for future generation, the world is now focusing on renewable energy sources (Kamil, 2010).In the last decade, the renewable energy sources have shown a worthwhile contribution in the energy sector of developed and some developing countries. It is unfortunate, that share of renewable energy is negligible in the energy sector of

Received date: 2015-05-25 **Accepted date: 2015-10-21**

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Pakistan. Therefore, it is ideal time to explore the abundantly available renewable energy sources in Pakistan to overcome this current energy crises. Sun is one of the most attractive alternate source of energy for water heating applications (Rahman, 2010). Pakistan has huge potential of solar energy (average value 5.3 kWh/m^2/d), which could play a vital role to mitigate the energy crises. Throughout the country, a significant amount of fossil fuel and electricity is being consumed for low to medium temperature heating applications in residential, agro-industrial, textile industry and processing plants. A cost effective renewable energy technology like solar water heaters with minimum danger and high returns is the need of residential areas (Guiney et al., 2006). To enhance the adoptability of solar water heaters in residential areas, its initial cost should be reduced with high market saturation (Kalogirou, 2004).Various types of solar thermal collectors i.e. non-concentrating collectors like vacuum tube collectors (VTC), flat plate collectors (FPC) etc. and concentrating type collectors like paraboloidal concentrators, heliostat etc.) are being used worldwide to produce low to high temperature solar thermal energy. Since, these collectors are mostly developed in advanced countries with high initial cost making it unaffordable to be purchased by developing countries. From various type of collectors, flat plate collector is simple in design and easy to develop, assemble and operate for low to medium temperature applications. The adoptability of flat plate collector on larger scale at domestic level could play a vital role for savings of huge amount of primary energy and reducing considerable amount of carbon emissions. In the light of above facts and benefits of solar thermal collectors, this research has been carried out to develop a flat plate collector using locally available material and manufacturing facilities to reduce its initial cost without compromising on its overall efficiency. The development of this low cost flat plat collector will be employed for variety of applications viz. sanitary hot water production, space heating of buildings, low temperature agro-industrial application, pre-heating of water for steam generation using boilers, drying and dehydration of agricultural products (Amrutkar et al., 2012).The major components of flat plate collector includes transparent cover glass, highly conductive absorber plate, highly conductive heat and water transporting tubes and insulation to avoid thermal losses. Flat plate collector as the name indicating is not always flat, it may be flat, curvy or wavy depending upon the design and requirements. It is called flat because it seems like a flat (Pravin et al., 2012). During the working principle of collector, the incident solar radiation is absorbed by absorber plate to convert it into useful thermal energy (Amrutkar et al., 2012). Flat plate collector is useful for domestic applications due to its simple design, easy to maintain and handle and mainly it falls in low to medium temperature range which is suitable for domestic applications and can serve up to 15 to 20 years (Pravin et al., 2012). The technology of the flat plate collector was introduced more than a century ago but still it has many flaws e.g. lower efficiency, higher thermal losses, and most importantly the higher initial costs and requires a large space for installation which makes consumers unwilling behavior to adopt and install this technology. Recently, different scientists have developed selective materials to increase overall efficiency of FPC by reducing thermal losses and increasing heat transformation from absorber to receiver. However, the use of these selective materials have increased its initial cost. Furthermore, most of these materials are not locally available. This study has be carried out to develop low cost 1 m^2 flat plate collector using locally available materials. The performance evaluation of collector has also been carried out in terms of its collection efficiency and energy production under local climatic conditions of Pakistan. The economic feasibility of flat plate collector in comparison with conventional water heating system has also been carried out for energy production in domestic and remote areas.

2 Materials and methods

The development and performance evaluation of flat plate collector has been carried out in the workshop of the Department of Farm Machinery and Power, Faculty of Agricultural Engineering and Technology, University of Agriculture Faisalabad (31.43 °N, 73.07 °E, and 190.76 m). The research work has been carried out in three different phases:

Phase-I:

During the first phase of the research, the basic collector design parameters were investigated. The research was focused on the development of 1m^2 flat plate collector for single family house. The collector consists of copper tube (coefficient of thermal conductivity as 398 W/m/K) having internal diameter and wall thickness of 4 and 0.4 mm respectively, an aluminum absorber plate (coefficient of thermal conductivity as 250 W/m/K) having length and width of 1120 and 920 mm respectively and thickness of 0.5 mm. Black matt paint was sprayed over the aluminum sheet as an absorber material. A 3 mm thick window glass is used as a cover glass having transmittance of 0.85. A 50 mm thick rock wool (coefficient of thermal conductivity range 0.0035-0.0043 W/m/K) was used to insulate the system to reduce thermal losses. The outer frame of the collector is made of wood due to its local availability, lower market price, durability and natural insulation property. The isometric view of different components of collector is shown in Figure 1. In Figure 1, (A) represents 3 mm cover glass, (B) is the wooden frame, (C) is a 0.5 mm aluminum absorber plate, (D) is a 4 mm internal diameter copper tube, (E) is a 50 mm thick rock wool insulation and (F) is the back cover of the collector. Referring Figure 2, after development of flat plate collector (1), a water storage tank (2) having capacity of 30 L was connected for water circulation and storage purposes via inlet and outlet pipes (4) & (3) respectively. A 60 W_p DC rotor pump (5) operated by PV module (6) and battery (7) was used for circulation of water between collector and storage tank. The system was equipped with thermometers for measuring inlet and outlet temperature of the water passing through the collector.

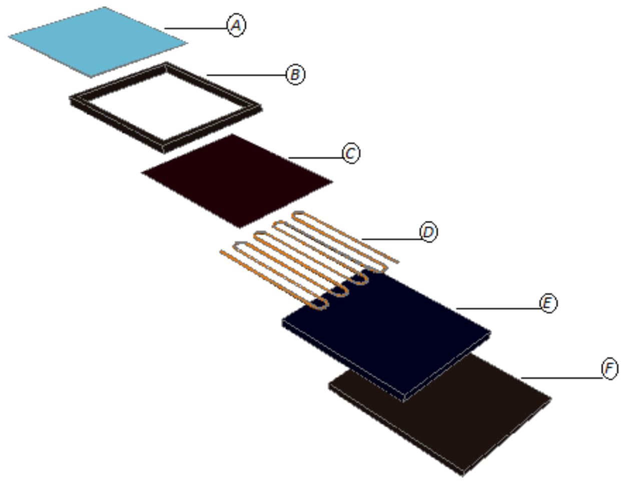

Figure 1 Isometric view of different collector components

Phase II:

During the second phase of the research, the performance evaluation of flat plate collector water heater (FPCWH) has been carried out to calculate its efficiency. The complete experimental layout is shown in Figure 2.

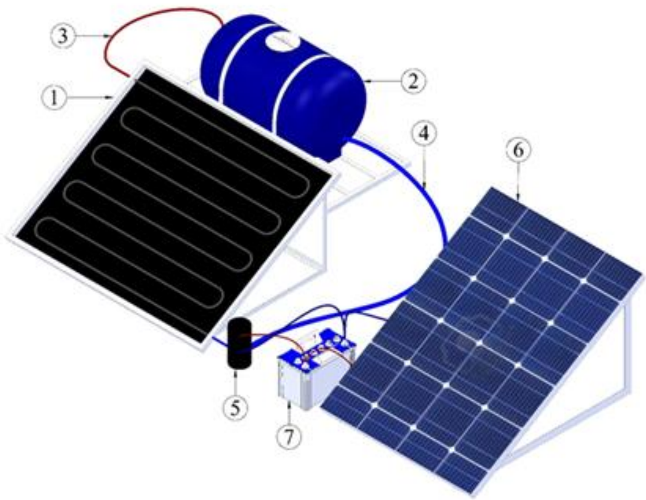

Figure 2 Experimental setup of flat plate collector water heater

The performance evaluation of collector was performed in terms of its efficiency and energy produced. The available energy during experiment was calculated using Equation (1).

$$Q_i = I_t \times A_c \quad (1)$$

Where: Q_i is total energy available in W, I_t is the available solar radiation in W/m^2 and A_c is the total area of the collector in m^2.The energy produced by the collector was calculated using Equation (2).

$$Q_u = \frac{mc_p\Delta T}{t} \quad (2)$$

Where: Q_u is the energy produced by the collector in W, m is the mass of water in kg, ΔT is the temperature difference in °K, C_p is the specific heat of water in J/kg/K and t is the time span in seconds. The efficiency of the collector was calculated using Equation (3).

$$\eta = \frac{Q_u}{Q_i} \times 100 \quad (3)$$

Where; η is efficiency of the collector in %, Q_u is the useful energy produced in W and Q_i is the energy available in W.

Table 1 shows the average data recorded during performance evaluation of flat plate collector.

Table 1 Parameters determined during performance evaluation of FPCWH

Sr. No.	Parameters	Values
1	Available average total solar irradiance (W/m^2)	833.90
2	Total mass of water (kg)	30
3	Average mass flow rate (kg/s)	0.015
4	Average temperature rise (°C)	45
5	Time span (s)	14400
6	Overall average energy produced (W)	392.53
7	Overall average efficiency of the system (%)	47.06

Phase III:

The economic feasibility is considered to be an important parameter in the selection and adoption of different technologies. The economics analysis has also been performed for solar thermal collector in comparison with conventional water heating systems. The payback period of solar thermal collector has been calculated to justify its economic feasibility.

3 Results and discussion

During the performance evaluation of solar thermal collector, different experiments were performed on daily basis between 10:00 to 14:00 from May to June. The data has been collected at optimum tilt angle of 31.43° to determine the efficiency of flat plate collector. Collector efficiency is the ratio of useful thermal energy produced to the available solar irradiation (Struckmann, 2008). Figure 3 shows the effect of time on storage tank temperature w.r.t solar radiation and mass flow rate on 21st of May. The figure shows that the rate of increase in storage tank temperature was higher in start of the experiment and becomes constant. This was due to the fact that the stored hot water was not consumed frequently.

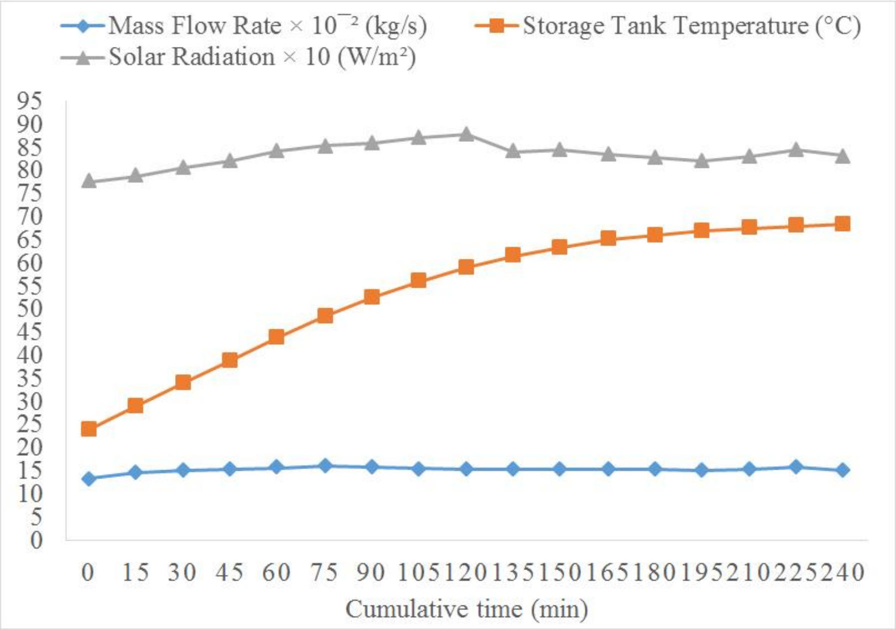

Figure 3 Effect of time on storage tank temperature

The efficiency curve between collector efficiency and reduced factor is shown in Figure 4. The reduced factor is a set of different parameters like ambient temperature (T_a), average inlet and outlet temperature ($T_{i,o}$), and solar irradiance (G). The reduced factor (Ω) is calculated using Equation (4).

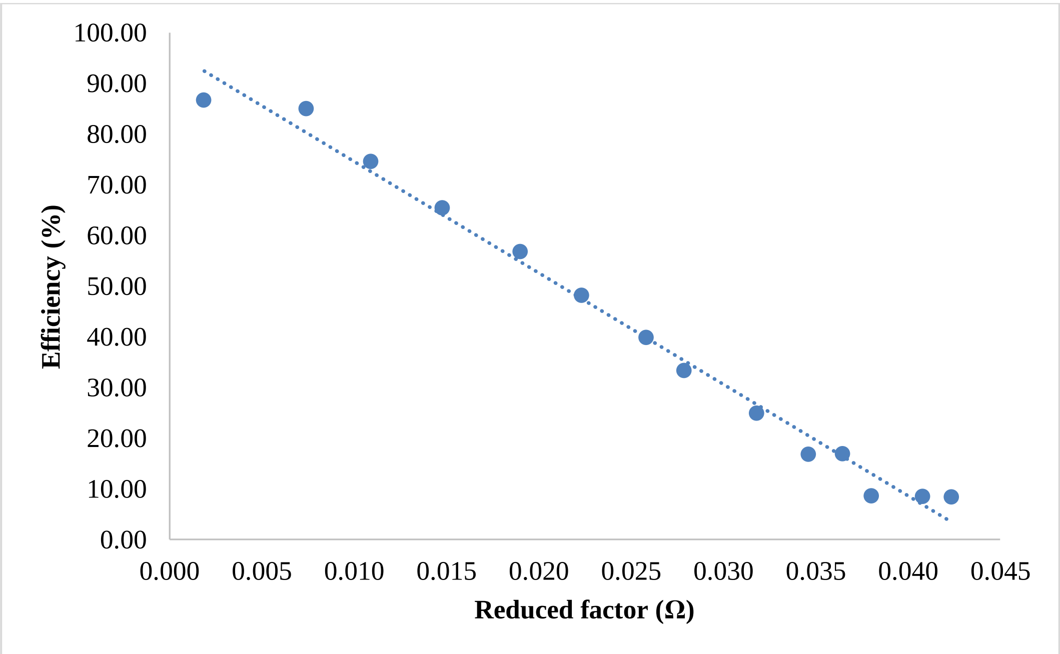

Figure 4 Efficiency curve of flat plate collector

$$\Omega = \frac{T_{i,o} - T_a}{G} \quad (4)$$

The efficiency curve of the developed FPCWH showed maximum efficiency (η) of 89.94% at the start when the fresh water passes through the collector during summer season when average ambient temperature was 42.41°C. The efficiency of collector decreases with the increase in the reduced factor and reaches to zero as expected. This is due to the fact that fixed amount of water in the storage tank was continuously circulated through the FPCWH.

4 Statistical analysis

The statistical analysis of the raw data was performed using Minitab 15 statistical software. Multiple linear regression analysis has been performed to determine the effects of cumulative time (CT), solar radiation (SR) and mass flow rate (MFR) on storage tank temperature (STT). The regression equation produced using this analysis is shown in Equation (5).

$$STT = -88.6 + 0.166\ CT + 0.141\ SR + 292\ MFR \quad R^2 = 0.97 \quad (5)$$

The above model explained that the unit change in variables i.e. CT, SR and MFR would change the mean value of storage tank temperature by 0.166, 0.141 and 292 times respectively while keeping other variables constant in the model. The high value of coefficient of determination (R^2) depicted the higher significance level of the model. The P-values of individual variable in Table 2 strengthened the results of Equation (5) indicating that two out of three variables CT and SR are lower than the significance level of α=1% while the third variable i.e. MFR showed non-significant result due to constant MFR.

Table 2 Multiple linear regression analysis of STT vs CT, SR & MFR

Predictor	**Coefficient**	**SE Coefficient**	**T- Value**	**P-Value**	
Constant	-88.61	24.66	-3.59	0.003*	
CT	0.16	0.01	15.67	0.000*	
STT	0.14	0.05	3.16	0.008*	
MRF	292	1973	0.15	0.884^{NS}	
Analysis of Variance					
Source	**DF**	**SS**	**MF**	**F**	**P**
Regression	3	3365.6	1121.9	128.61	0.000*
Residual Error	13	113.4	8.7		
Total	16	3479.0			

The effect of cumulative time on storage tank temperature was analyzed using first order quadratic model. The results depicted that the storage tank temperature was highly dependent on cumulative time. The higher value of R^2 showed the best fitness of the model as shown in Figure 3. The equation generated by best fitted line is shown in Equation (6).

$$STT = 23.34 + 0.4018CT - 0.000901CT^2 \quad R^2 = 0.99 \quad (6)$$

The results obtained using this analysis showed significant P values of sequential ANOVA (Linear & Quadratic) and falls under α=1% level of significance as shown in Table 3. Figure 5 shows that at the start of the experiment, STT increased with steep slope followed by the trend approaching to zero. The 1st derivative of the quadratic Equation (6) i.e. $\frac{dSTT}{dCT} = 0$, the CT was found to be 223. Later on, the trend can either decline or go straight (Figure 5)

Table 3 Polynomial regression analysis of STT vs CT

Analysis of Variance					
Source	**DF**	**SS**	**MF**	**F**	**P**
Regression	2	3476.19	1738.10	8583.16	0.000*
Error	14	2.84	0.20		
Total	16	3479.03			
Analysis of Variance					
Source	**DF**	**SS**	**F**	**P**	
Linear	1	3157.41	147.26	0.000*	
Quadratic	1	318.78	1574.22	0.000*	

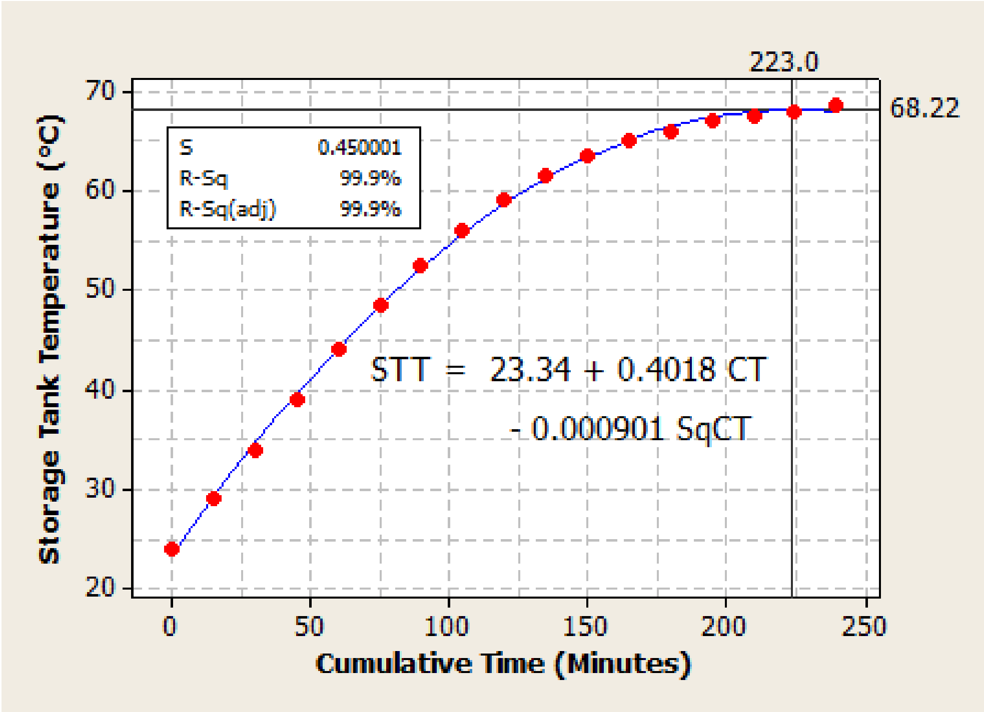

Figure 5 Effect of cumulative time on storage tank temperature

Simple linear regression model was better able to explain the effect of reduce factor (Ω) of different parameters on efficiency (η) of the collector as shown in Figure 6. The regression equation produced using this model is shown in Equation (7).

$$\eta = 100.3 - 2187\Omega \qquad R^2 = 0.97 \qquad (7)$$

Table 4 Simple linear regression analysis of efficiency vs reduced factor

Analysis of Variance					
Source	**DF**	**SS**	**MF**	**F**	**P**
Regression	1	14391.1	14391.1	503.14	0.000*
Error	14	400.4	28.6		
Total	15	14791.6			

5 Economics analysis of flat plate collector water heater

The economics analysis is the key factor for the adoption of a technology by the end-users. Figure 7 shows the comparisons of initial investment and seasonal operating cost of different water heating systems. The figure clearly shows that that forced circulation FPCWH including PV module system (in case of forced circulation) have around 40% higher initial cost as compared with other conventional water heating systems. Since, PV module is used for forced circulation of water which represents nearly 45% of the total cost of FPCWH system. The running cost per year of FPCWH is negligible while on the other hand gas fired water heater consumes natural gas and electric water heater consumes electricity to produce energy. The payback time of FPCWH was found to be 5-6 years considering expected life of the collector as 15 years.

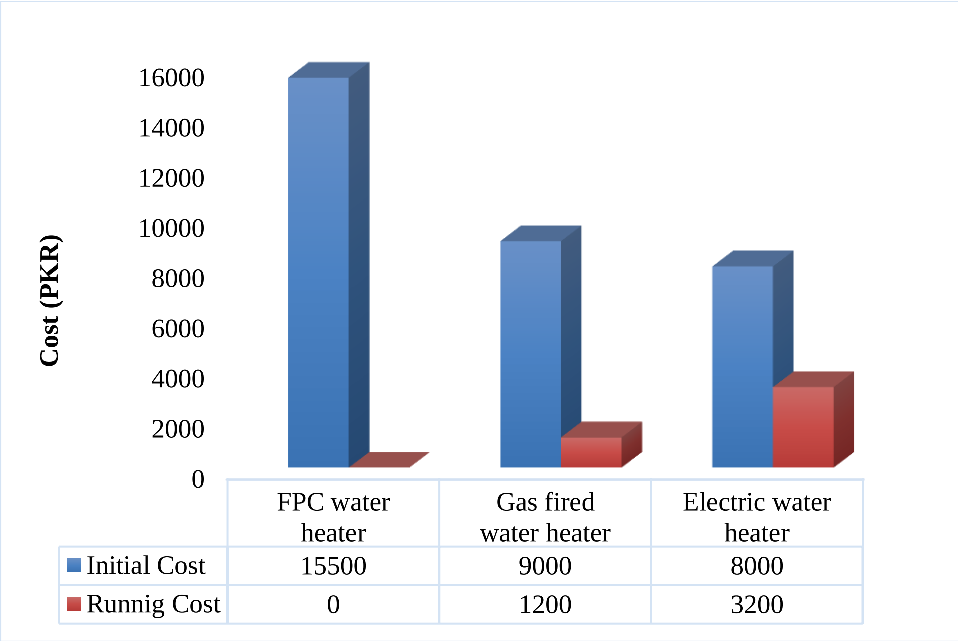

Figure 7 Initial investment and operating cost of different water heating systems

The comparison among the efficiencies of different water heating systems is shown in Figure 8. Standard errors of FPCWH, gas fired water heater and electric water heater were calculated as 7.73, 4.63 and 3.54 respectively. The results showed that there was significant difference between the efficiencies of FPCWH with other water heating systems. Although, the efficiency of FPCWH is lower as compared with other water heating systems, however, its renewable nature is more cost effective and environmental friendly in comparison to other conventional water heating systems.

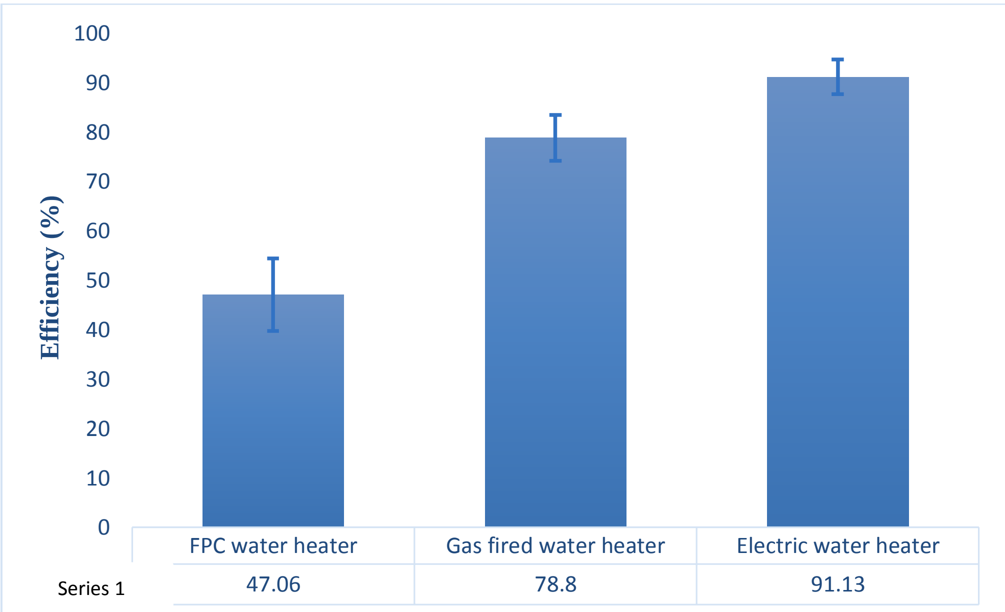

Figure 8 Comparison between efficiencies of different water heating systems with standard errors

6 Conclusions

Due to increasing energy crises, it is a high time to explore alternate energy sources of energy for sustainable energy supply in the country. A huge amount of fossil fuels and electricity is consumed in the generation of low to medium temperature thermal energy for domestic, agro-industrial and processing units. Very little work has been done for the exploration of renewable energy sources in Pakistan. Therefore, it is the need of the time to develop low cost local technologies to attract the end-users to adopt these environmental friendly technologies for the sustainable future of the country and world. This paper is focused on the development of a flat plate collector using locally available materials and infrastructure to reduce its initial cost and making it affordable and easily accessible to poor community members. During the development of FPC, window glass as cover material, aluminum collector sheet, and black matt paint as an absorber material, copper tubes, Rockwool insulation and a wooden frame was used. The performance evaluation of collector has also been carried out. The results showed that the overall average efficiency of the collector was found to be 47.06%. The expected life of the flat plate collector water heater is 15 years and the payback time lies between 5 and 6 years. It could be concluded that the design of local collector has reduced its initial cost without compromising on its average efficiency and can easily be used for domestic or agro-industrial processing applications especially in rural and remote areas having no access to natural gas or electricity.

References

Pakistan Energy Year Book. 2012. Ministry of petroleum and resources hydrocarbon development institute in Pakistan.

Kamil, N. M. Q. S. B. N. A. 2010. Performance evaluation of solar flat plate collector. Report submitted in Faculty of Mechanical Engineering, University Malaysia Pahang, Malaysia.

Rahman, A., A. S. M. Sayem, and A. Zaman. 2010. Alternative solar hot water system with multi storage tank. Thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Electrical and Electronics Engineering, Department of Electrical and Electronics Engineering, BRAC University, Dhaka, Bangladesh, 11-15.

Guiney, W. T., J. Harrison, S. Kaufman, and S. Milton. 2006. A guide for free service solar water heating programs for Caribbean electric utilities. *Green Markets International, Inc.*

Kalogirou, S. A. 2004. Solar thermal collectors and applications. *Progress in Energy and Combustion Science,* 30(3):231–295.

Amrutkar, S. K., S. Ghodke, and K. N. Patil. 2012. Solar flat plate collector analysis. *IOSR Journal of Engineering*, 2(2):207-213.

Gajbhiye, P.N., and R. S. Shelke. 2012. Solar energy concentration techniques in flat plate collector. *International Journal of Mechanical Engineering and Technology*, 3(3):450-458.

Struckmann, F. 2008. Analysis of a flat-plate solar collector. Project report 2008 MVK160 Heat and Mass Transport, Lund, Sweden.