Analysis of solar water heater with parabolic dish concentrator and conical absorber

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Abstract. This research focuses on developing novel technique for a solar water heating system. The novel solar system comprises a parabolic dish concentrator, conical absorber and water heater. In this system, the conical absorber tube directly absorbs solar radiation from the sun and the parabolic dish concentrator reflects the solar radiations towards the conical absorber tube from all directions, therefore both radiations would significantly improve the thermal collector efficiency. The working fluid water is stored at the bottom of the absorber tubes. The absorber tubes get heated and increases the temperature of the working fluid inside of the absorber tube and causes the working fluid to partially evaporate. The partially vaporized working fluid moves in the upward direction due to buoyancy effect and enters the heat exchanger. When fresh water passes through the heat exchanger, temperature of the vapour decreases through heat exchange. This leads to condensation of the vapour and forms liquid phase. The working fluid returns to the bottom of the collector absorber tube by gravity. Hence, this will continue as a cyclic process inside the system. The proposed investigation shows an improvement of collector efficiency, enhanced heat transfer and a quality water heating system.

1. Introduction

Limitation of fossil fuel and environmental issues has increased the demand on renewable energy. Through renewable energy, a country could optimize per capita energy consumption maintaining the environmental impact. Solar energy is one of the potential renewable energy and this could be used for domestic water heating [10-11]. Though solar powered water heating system comprising flat plate solar collector and parabolic dish solar collector have been well established, the heat transfer rate is low due to single faced heat absorber [13]. In order to solve such issue, a novel conical heat absorber solar collector water heating system will be developed. Conical heat absorber will be able to absorb heat from multi directions, and hence, enhance the heat transfer rate. It is expected that rate of heat exchange would be 20% higher than the flat plate solar water heater.

Normally this type shows better efficiency than flat plate type. The solar flat plate collectors and evacuated tube collectors [1-2] are used as water collector in the different climatic regions. In conventional flat plate collector solar water heaters, copper, or mild steel plate embedded with galvanized iron, mild steel pipes are used as absorber, and glass wool used as insulation material [3-5]. However, to supply hot water to domestic and industrial applications, only little efforts have been made to develop building integrated solar water heating technology [6-7]. Normally, in flat plate and vacuum tube water heaters, collector and storage tank are two separate parts. An integrated collector storage technique is adopted to make the system simple and economical [8]. In integrated collector storage solar water heater, solar collector and water storage tank are integrated as a single unit. It is simpler in construction, lower in cost compared to flat plate or vacuum tube thermosiphon type water heaters and capable of fulfilling hot water demand of 100-200 liters per day [9]. Zekai Sen [10] presented a comprehensive review of solar energy in progress and future research trends. Ong and Tong [11] experimentally studied the system performance of U-Tube solar water heaters and the paper reports the results of outdoor tests conducted on several evacuated U tube solar collectors under natural and forced convection.

Experimental study and analysis of parabolic trough collector with various reflectors has been investigated [12]. In this experimental setup, the reflected solar radiations were focused on absorber tube which was placed at focal length of the parabolic trough. The design and development of a parabolic dish solar water heater for domestic hot water application was investigated [13]. Their research the heater is to provide 40 liters of hot water a day for a family of four, assuming that each member of the family requires 10 liters of hot water per day. For effective performance, the design requires that the solar water heater track the sun continuously, and an automatic electronic control circuit was designed and developed for this purpose. The design, construction and study of frusto-conical solar collector were carried out using locally available materials [14]. The conical shaped concentrator was made from galvanized iron sheet with a thickness of 0.644 mm. The inner side of the cone shape with thickness of 10 mm was gummed with insulating foam material. A critical review on literature shows that considerable research has been carried out by many researchers on parabolic dish collector, flat plate, point focus, line focus and evacuated tube solar collector and mostly for urban usage. However, efficiency of those collectors is low due to unidirectional collection which leads to reduction in heat transfer coefficient. In this work, a novel solar water heating systems with conical heat absorber is proposed in order to accommodate multi directional solar collector. This would significantly contribute towards enhancing the collector efficiency through enhanced heat transfer rate providing the pave way to the usage in rural, domestic and industrial application.

2. System Description
The solar water heating system consists of a parabolic dish concentrator, conical heat absorber, water heater and water as a working fluid. A schematic of solar water heater with parabolic dish and conical heat absorber is shown in Fig 1. The experimental model is suitable for open ground to have a better view of the sun's radiation. The parabolic dish collector was constructed with aluminium sheet because of low weight, ease of fabrication and energy efficiency. To reduce the weight of the dish, a light glass mirror of 2 mm thickness, of high surface quality and good specular reflectance was used.

A glass mirror was selected over polished aluminium surface because its reflectivity of 95% is better than that of aluminium (85%). Also, glass surface is easier to clean than aluminium surface [15]. The spiral copper tube is used for circulation of vaporized working fluid in the heat exchanger (water heater). The reflecting solar radiations from the parabolic dish collector are focused on the conical absorber tube absorb the radiation from the solar, both joint together will give significant heat improvement on absorber tubes. In this setup, water is used as working fluid which collects heat from absorber tube to heat exchanger. Initially, the working fluid is stored at the bottom of the absorber tubes. Due to solar radiations the absorber tubes get heated, when the heat transfer inside the tube, increases the temperature of a working fluid inside of the absorber tube and causes the working fluid to evaporate.
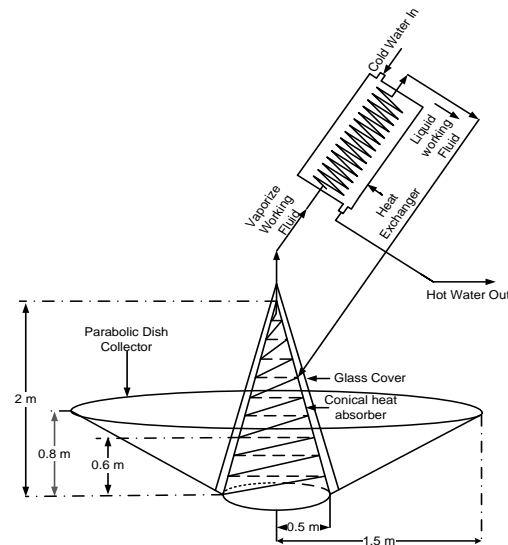
Figure 1. Schematic of solar water heater system.

Due to volume expansion and density gradient of air resulted from the buoyancy effect, the vaporize working fluid move upward direction and spontaneously enter to the heat exchanger. For extracting heat energy, the fresh cold water is circulated inside the heat exchanger which would decrease the temperature of the vapor and finally condensate the vapor to form liquid phase. Gravity driven working fluid returns to the bottom of the collector absorber tube. Hence, this will continue as a cyclic process inside the system. In this research, combined effect of conical absorber tube direct absorption and parabolic dish concentrator reflection from multi direction would provide better heat gain for solar water system compare to existing systems.

3. Analysis of Useful Heat Gain
The performance of collector could be determined by an energy balance that indicates the distribution of incident solar radiation into the useful energy gain and thermal losses. In order that the performance of the solar collector be as high economically practical design and operating factors that increases the solar heat flux absorbed and reduce the thermal losses are determined. Under steady condition, the useful heat collected by solar collector can be stated below [10].
Heat collected = Energy absorbed – Heat losses

$$Q_c = A_c[HR(\tau\alpha) - U(T_p - T_a)] \tag{1}$$

where

R	Conversion factor
A_c	Area of collector, m^2
H	Radiation incident rate, W/m^2
U	Overall heat loss coefficient, W/m^2K
Q_C	Heat collected from the solar collector
T_p	Tube temperature, $^\circ C$
T_a	Ambient temperature, $^\circ C$
α	Absorptivity
τ	Transmissivity

Alternatively the energy balance equation on the whole collector can be written as:

$$A_c[HR(\tau\alpha)_b + HR(\tau\alpha)_d] = Q_c + Q_L + Q_s \tag{2}$$

Collector efficiency is defined as the ratio of useful heat absorbed over solar radiation available over the collector surface.

$$\eta = \frac{Q_c}{A_c HR} \tag{3}$$

An attempt is made to drive the equations, which is used to describe the thermal performance of parabolic concentrator and conical absorber. The useful heat gain is the heat transfer rate to the fluid after considering all resistances and heat losses [15].

Useful heat gain to the fluid is obtained is,

$$Q_u = WLF_p \left(S - U\left(T_f - T_a \right) \right) \tag{4}$$

Useful heat gain collector efficiency is,

$$\eta = \frac{Qu}{A\ HR} \tag{5}$$

4. Analysis of Fluid

In this analysis, the energy balance is performed with three control volumes to study the temperature distribution and behaviour of fluid at subcooled, saturated and superheated regions. Consequently, it yields three differential equations as follows.

Subcooled condition:

$$\frac{dT_f}{dy} = \frac{WF_p}{\dot{m}_L C_{PL}} \left[S - U\left(T_f - T_a \right) \right] \tag{6}$$

Saturated condition:

$$\frac{d\dot{m}_v}{dy} = \frac{WF_p}{h_g - C_{PL} T_{f2}} \left[S - U\left(T_f - T_a \right) \right] \tag{7}$$

Superheated condition:

$$\frac{dT_{f3}}{dy} = \frac{WF_p}{\dot{m}_v C_{PV}} \left[S - U\left(T_f - T_a \right) \right] \tag{8}$$

The three differential equations are solved using the fourth Order Runge-Kutta method written in MATLAB program. To run the analysis and calculated the numerical values of some parameters. Using the predetermined variables, the validated differential equations are solved to numerically investigate the working fluid temperature distribution in subcooled, saturated and superheated regions. The data generated are plotted in graphs to show the correlation between the tube length and the refrigerant temperature along the tube. Figure 2 illustrates the temperature distribution of water along the heated tube from 20°C to 80°C. It covers the three regions as mentioned above. The working fluid temperature at the inlet is 20°C. The heat energy from the absorber increases the temperature of the subcooled liquid from 20 to 58°C in 1.58 m. At the saturation point, the refrigerant starts to evaporate at constant temperature at corresponding saturation pressure. The distance needed for the evaporating refrigerant (working fluid) to reach superheated region is 6.17 m. From there (at about 7.75 m from the tube inlet), the superheated refrigerant experiences a rise in temperature to a pre-set limit of 80°C. Besides, as expected the length needed for sensible heating in subcooled and superheated regions are relatively short as compared to the length needed for liquid evaporation.

The analysis has found three governing parameters which determine the dimensions and performance of the solar collector and these factors could be ranked based on their dominant effect on the solar collector. The governing parameters are, mass flow rate, overall heat loss coefficient and solar heat flux. An investigation on equation (4) gave a clear explanation. Increased the mass flow

increases the tube length needed to superheat the liquid refrigerant. Figure 2 shows the result when the flow rate is increased from 0.010 kg/s to 0.018 kg/s while retaining other parameters. The result shown the length needed is about 80m. Although the working fluid will reach the required temperature at the end, the collector area is far too high.
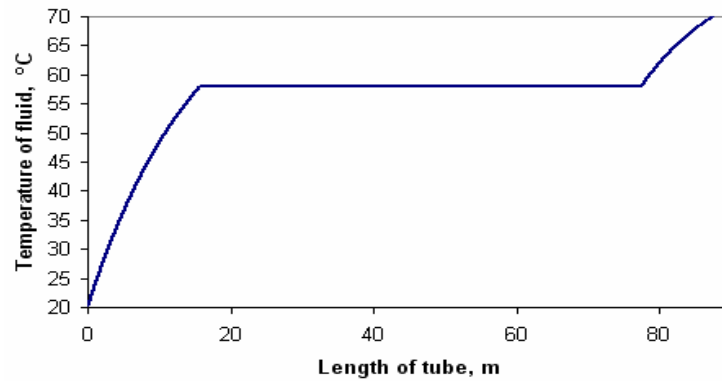

Figure 2. Temperature distribution of working fluid, when the mass flow rate is increased.

Similarly while retaining other variables reduced heat loss coefficient allows better absorption of heat energy in the collector. Equation (4) shows higher overall heat loss coefficient, U increases the heat loss product which results in greater reduction of heat energy collected. From Figure 3, the heat loss coefficient which is reduced from 8 to 4 W/m^{2}K by incorporating double glazing (16) into the collector increases the heat energy inside the collector and thus the tube length needed for the whole process is relatively short in comparison to the single glazing flat-plate collector.
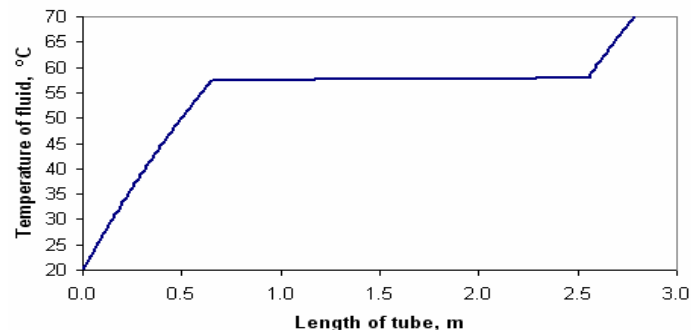

Figure 3. Temperature distribution of working fluid, when the overall heat loss coefficient is reduced.
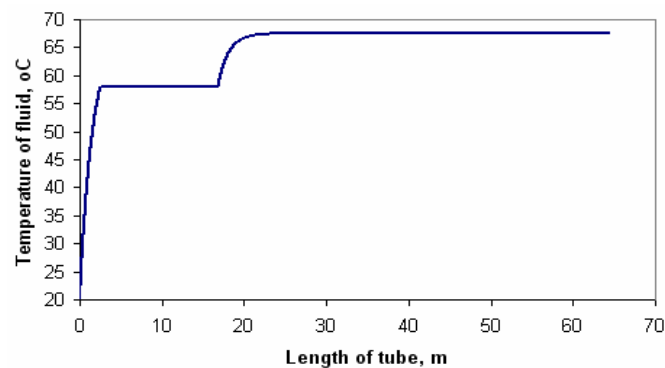

Figure 4. Temperature distribution of working fluid when solar heat flux is reduced.

In Figure 4 shows the similar effect is anticipated with the decrease of solar heat flux quantity. This three factors the solar heat flux is the most dominant factor that governs the potential and practicality of the solar collector. Though the performance of the collector is very much affected by the changes in mass flow rate and overall heat loss coefficient, insufficient solar heat flux close the system down totally. As shown, the reduction of solar heat flux from 400 to 300 W/m^2 altered the refrigerant temperature distribution pattern and the effect is even greater with lower solar heat flux.

Apart from the governing parameters, reducing the thermal resistances in collector efficiency increased the performance of the collector. From calculations the thermal resistance for a thin tube wall of good thermal conductivity and for the bond is almost negligible. Fouling resistances due to scale formation is about 0.01061 K/W and the fluid film resistance is about 0.0796 K/W. As assumed that the collector is well bonded and made from high thermal conductivity material, the tube thermal resistance is the most dominant factor in the collector performance which is about 0.8651 *K/W*. For this reason improving the tube design and material could extensively enhance the collector efficiency regardless of other minor thermal resistances. Though the ambient temperature is an uncontrollable factor, the fact that it varies with time and with geographical location means that collector efficiency depends on this factor as well.

From the specific heat transferred to the working fluid in the conical absorber and the specific heat transferred from the working fluid in the water heater are found using the following formulas [17].

Mass flow rate of cold water (kg/s) entering inside the water heater

$$m_{cold} = \frac{Q_{cond}}{[Cp_{water}(T_{c2} - T_{C1})]} \qquad (9)$$

heat transfer rate (kJ/s)

$$Q_{cond} = m_C(q_A) \qquad (10)$$

Surface area of the Condenser (m^2)

$$A_{cond} = \frac{Q_{cond}}{\{U_{heater}[(T_1 + T_4)/2 - (T_{c1} + T_{c2})/2\}} \qquad (11)$$

Where

T$_1$ Temperature of vaporized working fluid entering the water heater
T$_2$ Temperature of partially condensed working fluid exiting from the water heater
T_c Temperature of the cold water entering the water heater
T_h Temperature of the hot water exiting the condenser

5. Result and Discussions

The first experimental study focused without parabolic dish concentrator and second experiment study focused with parabolic dish concentrator. Finally, the both experimental results are used to calculate the efficiency of the overall system and compare the efficiency of the both model. Figure 5 and 6 shows the variation of temperature and solar radiation for continuous time of two days experiment the month of August in Miri, Malaysia. Figure 5 results for without parabolic dish concentrator and Figure 6 results for with parabolic dish concentrator respectively. The water temperature, atmospheric

temperature and solar radiation results are similar for both cases, so when comparing the efficiency of both cases will give reasonable outcome in this study.

Figure 7 shows the outlet temperature of water for with parabolic and without parabolic solar concentrator. The difference between the two cases differed by around 20 %. It is observed that parabolic dish concentrator will help to improve the temperature of the absorber tube. Combined effect of conical absorber tube direct absorption and parabolic dish concentration from multi direction would provide better heat gain for solar water system compare to without parabolic dish concentrator.
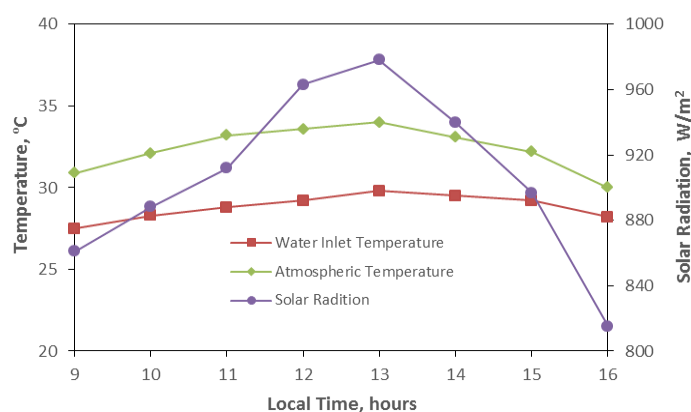

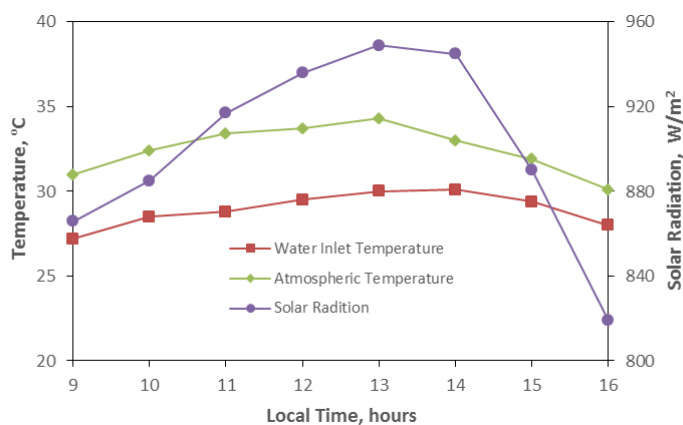**Figure 5.** Variation of Temperature and solar Radiation for time of day (hours).

Figure 6. Variation of absorber tempertaure without conical collector for time of day (hours).
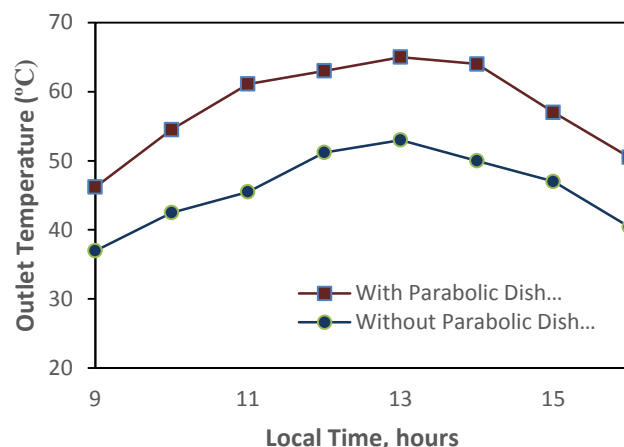
Figure 7. Variation of water hetar outlet temperature for time of day (hours).
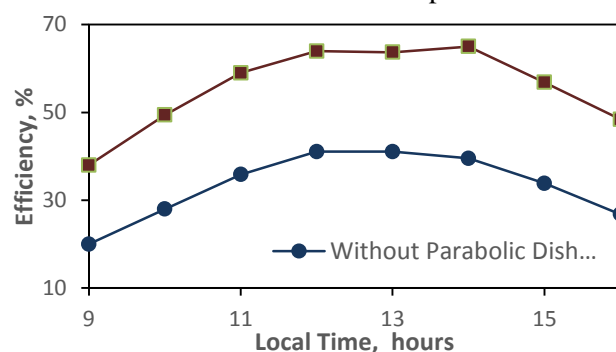

Figure 8. Efficiency of solar collector with and without parabolic for times of day (hours).

Comparison of the both experiment analysis with parabolic and without parabolic dish system efficiency is shown in Figure 8. The first day (9 to 16 hr) experiment without parabolic dish concentrator the average efficiency is 33.25% and the second day (9 to 16 hr) with parabolic dish concentrator average system efficiency is 55.40%. The difference between the two system differed by around 22.00%. The two continuous day experiment, in a particular time the maximum efficiency was achieved 65.00% for with parabolic dish concentrator and 41.00% achieved for without parabolic dish concentrator. The above system efficiency difference shows the unidirectional collection leads better collector efficiency than normal solar collector.

6. Conclusion

The analysis used in this paper is an alternative method of water heating from renewable energy resource with the use of parabolic dish concentrator and conical absorber. The heat transfer analysis performed in this paper is an effort to obtain the useful heat gain which governs the fluid temperature distribution along the tube. It has been concluded that the potential and practicality of the solar collector is dominantly influenced by many factors such as; solar collector area, absorber tube arrangements, the solar heat flux, mass flow rate and overall heat loss coefficient. The generation of maximum 65.00 % efficiency achieved for with parabolic dish collector and 41.04 % efficiency achieved for without parabolic dish collector. The difference between the two system differed by around 23.96 %. Combined effect of parabolic dish and conical absorber would provide better heat gain for solar water heating system. To work out large amount of hot water from heat energy source, a parabolic dish collector and conical absorber is an extremely attractive option.

References

[1] Chow T T, Dong Z, Chan L S, Fong K F and Bai Y *2011 Energ. Buildings* **43** 3467–3474.

[2] Hang Y, Qu M and Zhao F 2012 *Energ. Buildings* **45** 181–188.

[3] Zondag H A 2008 *Renew. Sust. Energ. Rev.* **12** 891–959.

[4] Sopian K and Zulkifli R 2002 *J. Mater. Proc.Technol*. **123** 179–184.

[5] Bilgen E and Richard M A 2002 *Solar Energ*. **72** 405–413.

[6] Nahar N M 2003, Year round performance and potential of a natural circulation type of solar water heater in India, *Energ. Buildings* **35** 239–247.

[7] Sowmy D S and Prado R T A 2008 Energy and Buildings, 40, 2128–2132.

[8] Souliotis M and Tripanagnostopoulos Y 2008 *Renew. Energ*. **33** 846–58.

[9] Tripanagnostopoulos Y, Souliotis M and Nousia T H 2002 *Solar Energ*. **72** 327–50.

[10] Zekai S 2004 *Prog. Energ.Combust. Sci.* **30** 367–416.

[11] Ong K S and Tong W L 2012 *J.Appl.Sci.Eng.* **15** 105-110.

[12] Avadhesh Y, Manoj k and Balram 2013 *Int. J. Physical Nat. Sci. Eng*. **7** 1-5.

[13] Ibrahim L M 2012 *Int. J. Eng. Res.App*. **2** 822-830.

[14] Vijayan G, Sebastian M V, Umarani K and Karunakaran R 2013 *Int. J. Eng. Res.Technol.* **2** 1220-1226.

[15] Ballaney P L 2003 *Thermal Engineering* Khanna Publishers Delhi.

[16] Goswami D Y, Kreith F and Kreider J F 2000 *Principles of Solar Engineering* Taylor and Francis USA.

[17] Nguyen T, Johnson P, Akbarzadeh A , Gibson K and Mochiziki 1994 *J. Heat Recover. Syst. CHP* **15** 333-346.