Paper ID: RT 237

Design and Performance Study of a Circular Flow Channel Solar Water Heater

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Abstract

The flow structure in a circular plate solar collector storage device, with circulation of the storage water inside circular pipe is studied experimentally using a constructed solar collector. Substantial circular plate solar collector efficiency improvement has been obtained employing circular flow conduits and using obstacles inside flow channel for making turbulence. Eventually solar radiation, solar absorption, stimulation of absorption which pertains with absorber material (copper), making of greenhouse effect by glass cover and black coating having maximum absorption and minimum reflectivity (around vantablack), making of turbulent flow, minimization of heat loss etc. influence the collector efficiency, and energy consumption are discussed. At length overview of this paper demonstrates overall thinking about design, cost, efficiency, and economical aspects. After completion of the apparatus through modification and experimentation it achieved the maximum thermal efficiency of 49.75%.

Keywords: Solar collector, stimulation of absorption, Obstacles, Turbulent flow, Thermal efficiency.

1. Introduction

The economic viability of solar thermal technology in the rapidly developing free energy market environment will be based on its competitiveness against conventional energy. The cost reduction of solar heating plants should be based on drastic cost reduction of the collector field subsystem. Now-a-days while more convenient energy sources like coal, gas, oil or any other fossil fuel are reducing their resources and at the same time – harming adversely to the atmosphere. Solar radiation applications are predominantly used and can be categorized into many developments in engineering such as solar heating. In this situation, solar energy can plays a vital role on energy convenience. Solar energy is a renewable energy source which in human time frames has a long life for energy output and therefore an almost infinite energy source. Solar energy could supply the world's foreseeable energy needs, meanwhile, with the highest technical potential as compared with other renewable energy sources (i.e. biomass, wind, hydroelectricity, geothermal and etc.) The fascination of renewable energy is that it is not dwindling or reducing its intensity and it does not damage environment and rather it contributes towards a pollution free environment where conventional energy sources are costly and results in by-producing harmful emission of exhaust to environment and causing the climate change by increasing temperature. Solar radiation is produced by the nuclear fusion of different elements inside the sun (basically conversion of Hydrogen and Helium nucleus) and this radiation emits in the form of sunlight, infrared rays, ultraviolet rays, cosmic rays, x-rays etc. The rate of solar emission from the sun is 4.3×10^9 kg/sec. The power from the sun intercepted by the earth is approximately 1.8×10^{11} MW [1]. Most of the sun's energy that makes the 93,000,000-mile journey is in the form of visible and ultraviolet light.

In coastal region of Bangladesh solar radiation varies from 6-11 hours daily [2] as location of Bangladesh lies between $20\mathbf{0}°$ 30´ and $26\mathbf{0}°$ 45´ north latitude and has a total area of 1.49E+ $11m^2$. An average of 5 kWh/m^2 solar radiation falls on this land over 300 days per annum. This larger amount of solar radiation can be used to produce at least 22.2-28.5×10^8 MW power per annum [3, 4]. The Bangladeshi Govt. is working towards universal power access by 2021 with SHS programs projected to cover 6 million households by 2017 [5]. The World Bank has called it "the fastest growing home system program in the world".

Actually, the circular plate solar collector is mechanically and technically simpler than the types of solar collector in transforming solar radiant energy into heating a passing fluid. Water heating typically demonstrates a high percentage of energy consumption in homes and businesses, in some cases 30% or more[6].
In this inspection experiment appraisal recline collector efficiency of solar water heater with circular conduits configuration with rectangular obstacles inside and simulation analysis. In several investigations, circular shaped device is designed as conduits for increasing heat-or mass-transfer efficiency. Internal circulation enhances the heat-transfer rate in solar water heaters, resulting in improved device performance, as concluded from previous literature. Water flows through channels attached to the absorber and picks up the heat from it where most of the solar radiation is absorbed and converted to heat. Furthermore flow in channels can also be linear or turbulent and for turbulent flow obstacles in the circular flow channel which will be more efficient. To improve solar water heaters thermal performance, many investigators proposed various strategies such as reducing the heat loss from the collector, creating of fluid turbulence pasting the heating surface, extending the heat-transfer are, increasing the absorptivity of absorber, and optimizing the design parameters such as various conduit cross area and absorber plate materials [7]. This paper theoretically and experimentally investigates the collector efficiencies of solar water heater with circular conduit cross sections. The effect of circular concept is used to increase the convective heat-transfer rate. The flow conduit aspect ratio, incident solar radiation, inlet water temperature, number of circular channel, fin efficiency factor, and water mass flow rate on collector efficiency are discussed. In comparison with collectors of the concentrating type, such as those used in high temperature solar-furnace applications, circular plate collectors offer these advantages: (1) No complicated mechanisms for flowing. (2) Construction is simple and cost is relatively low. (3) Diffuse as well as direct solar radiation is utilized.

2. Design and Fabrication of the Solar Water Heater

2.1 Design of the collector

The governing equation of a solar collector is [8]
$\frac{Q_u}{A_c} = F_p[I_T(\tau\alpha) - U_L(T_{mean} - T_{amb})]$ Where, overall heat transfer co-efficient is

$U_L = U_t + U_b + U_s$=Top, Bottom and Side Loss Coefficient [9]:

Here is an empirical equation for calculating top heat transfer coefficient by

$$U_t = \left[\frac{N}{\left(\frac{C}{T_m}\right)\left(\frac{T_m - T_a}{N+f}\right)^{0.525}} + \frac{1}{h_w}\right] + \frac{\sigma(T_m^2 - T_m^2)(T_m + T_a)}{\left[\frac{1}{\varepsilon_p + 0.0425N(1-\varepsilon_P)} + \frac{2N+f-1}{\varepsilon_g} - N\right]}$$

Where, N = Number of glass cover = 1
Here, β = 24° (Collector tilt from horizontal) [10], L= about .5 cm (spacing between the circular pipe)
C is the constant depending on tilt angle & space between collector plate & glazing material
$f = .5746$, Where, $h_w = 11.8$ W/m^2-K
V = Velocity of air over collector plate= 3m/s (average)
h_w = Heat transfer co-efficient of the wind, W/m^2-K ε_p= .96, ε_g = .07
Ta = Ambient temperature
Tb= Outlet temperature of water
Tm= Mean temperature
σ= Stephen-Boltzman constant= 5.67×10-8 W/m^2-k^4
So now from equation, U_t=2.26 $U_b = \frac{k_i}{l} = 4$
Where, k_i=thermal conductivity of cork board
Assume, $U_s =$ .034 W/m^2 –K [11]; Now, $U_L = U_t + U_b + U_s$ = 6.294 W/$m^2 - K$

Fig. 1.1 shows the prepared design of solar water heater with obstacles inside for making turbulence.

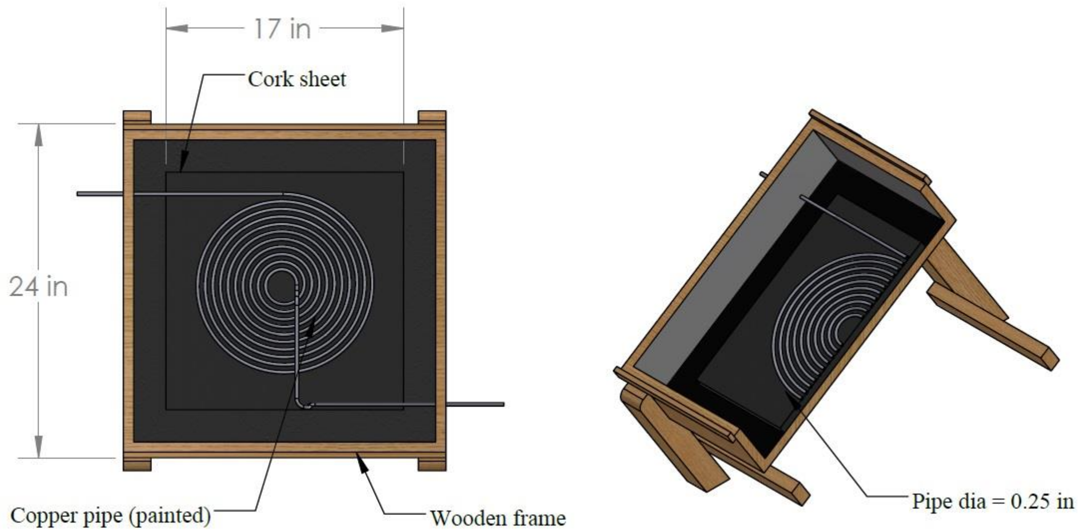


Fig. 1.1 Design of the collector and cross section of the collector

Collector Efficiency Factor (FP) [12]

$$F_p = \frac{\frac{1}{U_L}}{W\left[\frac{1}{\pi D h_{ft}} + \frac{m_t}{\pi D k_t} + \frac{1}{c_b} + \frac{1}{U_L[D + (W - D)F]}\right]}$$

F = fin efficiency factor given as

$$F = \frac{tanh\left[\frac{a(W-D)}{2}\right]}{\frac{a(W-D)}{2}}$$

Where, $a^2 = \frac{U_L}{K_p M_p}$

F = .849 W/$m^2 - K$

Now, $F_p = .85\ (Cu)$ Now from equation,

$$\frac{Q_u}{A_c} = F_p[I_T(\tau\alpha) - U_L(T_{mean} - T_{amb})]$$

= 578.27

$Q_u = 578.28\ A_c$

Heat taken or absorbed by water

$$Q_w = \dot{m}c_p(T_{out} - T_{in})$$
$$= 756 \text{ W}/m^2$$

A_c = 1.31 × (1000÷3600) m^2 = .3639 m^2

2.2 Fabrication of the solar water heater

Considering the length of collector plate is

Total length = 4.5 m; Pipe diameter = 0.00635 m; number of flow channel = 10

Central distance of each successive channel =.01 m

Distance of each successive fin (obstacle) = .1524 m

Length of a fin (obstacle) = .003048 m

Width of a fin (obstacle) = .001524 m

2.3 Collector thermal efficiency

Now Collector efficiency can be measured by the following equation

$$\eta = \frac{Q}{A_c I_T} = \frac{\dot{m} c_p (T_{out} - T_{in})}{A_c I_T} = \frac{4 \times 4.2 \times 1000 \times (78-33)}{.3639 \times 1160 \times 3600} = 49.75\ \%$$

2.4 Solar water heater with rectangular obstacles

The flat plate collector consists of an absorber plate which is consist of several circular channel with rectangular obstacles inside, on which the solar radiation falls after coming through a transparent cover made of glass. The absorber pipe is coated with black paint that absorbs a high fraction of the solar radiation falling on it. Internal fins causes turbulent and vortex flow. Thus conducted heat rises the water temperature. The density of water decreases as its temperature increases and so the density of outlet water is lower than the density of water at inlet. Generally performance of a solar water heater depends on the design, materials and also coating used for it.

Fig. 1.2 Constructed Solar Water Heater

2.5 Absorber pipe

Absorber pipe absorbs the solar radiation and transfer the resulting heat to the working fluid. Criteria that determine the choice of absorber plate material are:

- Good thermal conductivity, Corrosion resistance, Antimicrobial and Easily joined
- Ductile ,Tough and Catalytic
- Cost, Durability and Ease of handling

Thermal conductivity of different materials are investigated like Silver, copper, aluminum show high thermal conductivity and they are available in our country. The thermal conductivity of silver is 407 W/m/C, copper is 398 W/m/˚C and aluminum is 237 W/m/˚C. For the high price of silver, it is not chosen for the project. On the contrary copper is less expensive than silver although it shows more thermal conductivity, for the sake of the research work.

2.6 Absorber pipe coating

An antireflective coating is coating applied to the surface to reduce reflection and for maximum absorption in case of heat collector. Black coating is commonly used for better absorption properties among others. Now-a-days black chrome (chromium oxide) is also used as absorber coating. But it absorbs 96% solar radiation where black paint absorbs 98%. Additionally if we heat black paint up to 750ºC then it will converted to vantablack which will absorb 99.967% heat falling on it. So for better absorption of heat vantablack (around) is used.

2.7 Insulation

Insulation is done to reduce heat losses from the collector as well as absorbing channels of the solar water heater. Due to the availability, low cost, good thermal insulation cork board is used as insulator.

3. Results and discussion

This analysis was performed to investigate the effect of spiral pipe and putting rectangular fin inside the pipe in a flat plate collector. To perform this investigation, experimental data was collected using the improved designed collector in sunny days at RUET, Rajshahi, Bangladesh**.** As the efficiency of a flat plate solar collector depends on the solar intensity, the more the intense heat on absorber plate, the more the efficiency. In Rajshahi, average solar intensity is 1000 W/m^2 for one year. Modification of the collector is addition of obstacles internally for which turbulence is created and it stimulates the heat absorption. For improved system design with better painting and insulation, thermal efficiency was expected to increase. The Figures (2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.7 and 2.8) show experimental analysis for mass flow rate of 4 kg\hr. 5kg\hr. and 6kg\hr. The Fig. 2.1 shows that temperature difference rises as the gradual increasing of day time up to 11am to 12.30pm and then it gradually decreases as the solar intensity. Thermal efficiency is gained for maximum solar intensity at day 16.09.2017 at 11.30 PM. It was found from the experimental results that the thermal efficiency was maximum of 49.75%.

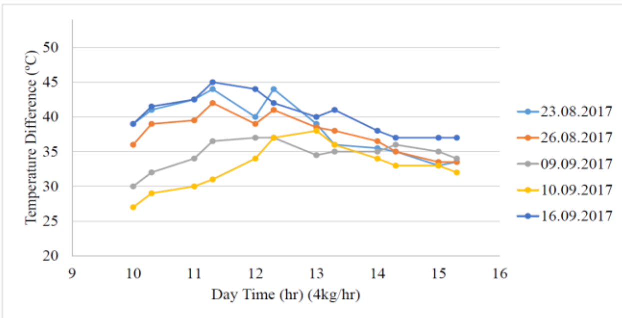


Fig. 2.1 Temp. Diff. VS Day time (4 Kg\hr.)

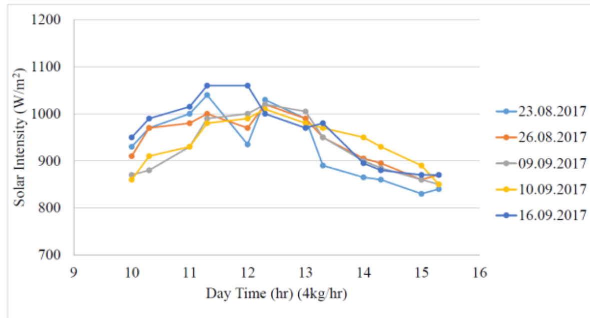


Fig. 2.2 Solar Intensity VS Day time (4 Kg\hr.)

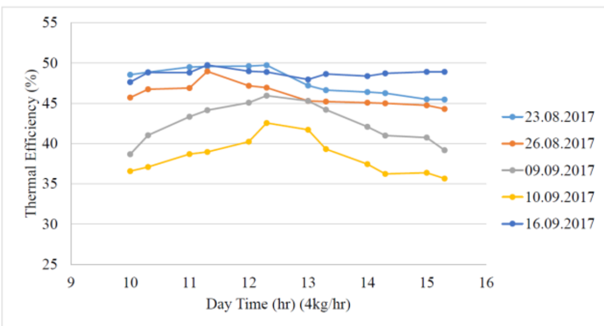


Fig. 2.3 Thermal Efficiency VS Day time (4 Kg\hr.)

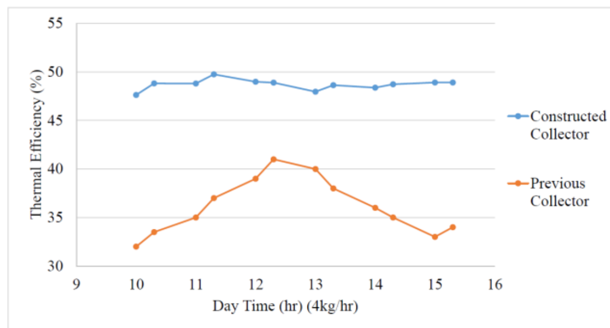


Fig. 2.4 Thermal Efficiency VS Day time (4 Kg\hr.)

A comparative analysis between previous collector and improved current one [Fig. 2.5] shows that the thermal efficiency difference between improved collector and previous is increased by more than 8%. It was the effect increase of residence time for the spiral pipe flow and turbulence created by the obstacles (fin).

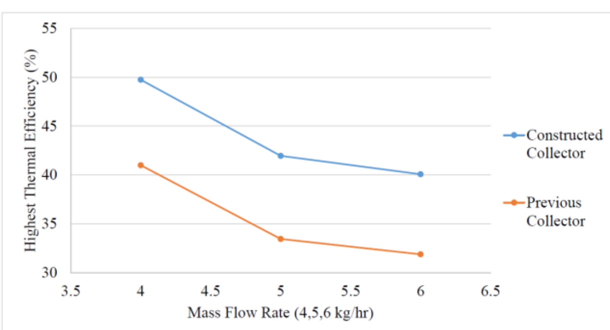


Fig. 2.5 Highest Thermal Efficiency VS Mass Flow Rate

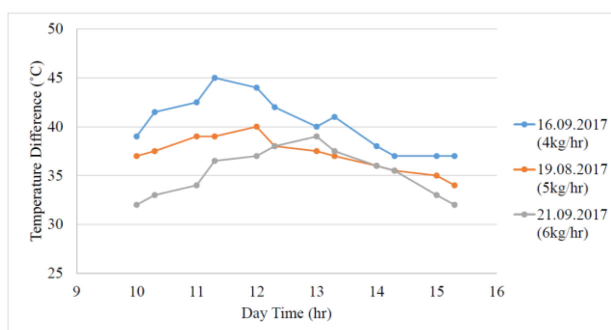
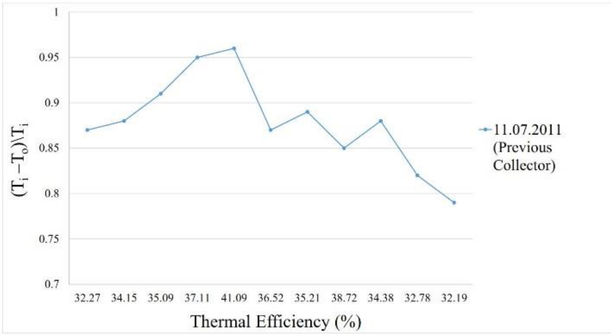


Fig. 2.6 Temperature Diff. VS Day time

The Fig. 2.5 shows the highest thermal efficiency VS Mass flow rate for 4, 5 and 6 kg\hr. for constructed and previous collector. It is seen from Fig. 2.6 that temps. Difference is higher for lower mass flow rate and a little lower for 5 and 6 kg\hr. mass flow rate.



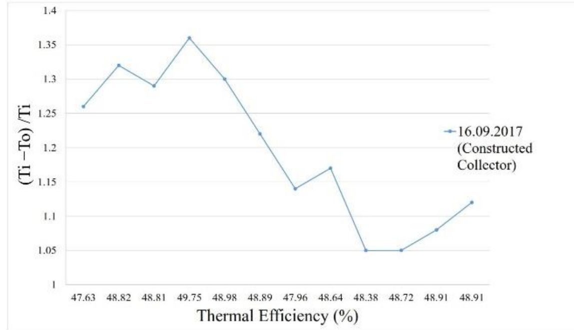


Fig. 2.7 $(T_i - T_o)\backslash T_i$ vs. Thermal Efficiency (4kg\hr.)

Fig. 2.8 $(T_i - T_o)\backslash T_i$ vs. Thermal Efficiency (4kg\hr.)

The Fig 2.7 and Fig. 2.8 shows the $(T_i - T_o)\backslash T_i$ vs. thermal efficiency for 4 kg\hr. for previous and constructed collector. It is seen from Fig. 2.7 and Fig. 2.8 that variation of temperature difference between the inlet and outlet by inlet temperature for the previous collector was not more than unity. For the constructed improved one it is about 1.36 where for the previous one it is .96. Overall the improved constructed collector gives better performance than the previous one.

4. Conclusion

In this project, a circular shaped solar collector with rectangular flow obstacles was designed, constructed and tested for performance analysis. The performance of the designed collector was analyzed with different mass flow rate at every day light hour. Investigations showed that, the maximum temperature of the outlet water was 78°C with an inlet temperature of 33°C at a mass flow rate of 4kg/hr. At the same condition, the maximum thermal efficiency was 49.75 %. A conventional collector of same collector area but different design was showed a thermal efficiency of 39.09 % [13]. Therefore, an enhancement of thermal performance was observed for the proposed one.

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