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Experimental Investigation of a Hybrid Evacuated Tube Solar Collector

J Ferdous[1], R A Beg[1] and M R I Sarker[1]
[1]Department of Mechanical Engineering,
Rajshahi University of Engineering and Technology, Rajshahi-6204
E-mail: jfe092016@gmail.com

Abstract

This paper presents the design, construction and experimental study of a hybrid type evacuated tube solar collector. This evacuated tube solar collector is engaged with an air cooling system to assist in heating the compressed working fluid using solar energy. This process reduces the compressor power and so the annual electric bill consumption by an air cooler will also reduce ultimately. In this study, an evacuated tube solar collector was constructed and experimentally tested. Copper made evacuated tubes and an insulated flat plate collector was used to construct this hybrid evacuated tube solar collector. Methanol was used as a heat transfer fluid. It was passed through the heat pipe to carry the absorbed solar energy. The results obtained from the experimental investigation show that the thermal efficiency of the collector was 29.17%. The energy obtained from the collector is capable to reduce the compressor power of the air cooling system and results in an improving in the whole system efficiency.

Keywords: *Solar collector, Evacuated tube, Methanol.*

1. Introduction

One of the promising sources for diminishing energy crisis is to make more extensive use of non conventional source of energy derived from the sun. It is known to us that renewable energy source is available in amount throughout the world in adequate quantity and of cost. Owing to increasing need for renewable energy sources, the investment for solar collectors' use is growing day by day. Recently evacuated tube collectors are most extensively used device to convert solar radiation into heat. Miscellaneous working fluids (methanol, ethanol, acetone etc) can be used in the heat pipe and varying results can be obtained for each.

The main motivation behind this concept came from ideas of evacuated tube solar collector as a novelty of this thought in our country. Several countries in the world are now enjoying the blessings of solar energy by utilizing it in reduction of electrical energy consumed by electrical machines. Some of the companies developing evacuated tube solar collectors are Apricus [1], SunMaxx [2] and Northern Lights [3] etc. These collectors are available in a range of sizes. The heart of the evacuated tube solar collector is heat pipe. A heat pipe can be considered as an evaporating and condensing device for rapid heat transfer. An evaporating-condensing cycle is employed by the heat pipe collecting heat from an external source. This external heat source increases liquid to its boiling point. A water based liquid in the heat pipe absorbs it's latent heat of vaporization when sun rays fall on it .The liquid releases its latent heat of vaporization in the condenser region when it comes into contact with the flowing liquid through the header. In this way the latent heat of vaporization is transferred. This process is repeated continuously by a gravity return feed mechanism of the condensed fluid back to the heating zone [4].

Both the radiative and convective losses are suppressed by the selective surface and vacuum inside of the heat pipe. Loss of vacuum is only at the side of a glass-to-metal permanent seal or an all-glass seal. Even if vacuum is lost, in a few of many tubes, performance of the entire collector decreases slightly. It is fully protected from oxidization, moisture, or any other form of attack as the black coating is inside the evacuated space in all designs. The glass tubes design are simple [5]**.** Evacuated tube collectors normally have a smaller fraction of total occupied area actually intercepting solar radiation compared with the most flat plate designs. Spacing between tubes, areas required for manifolds, and piping access all require space, which limits coverage by solar absorbing surface [5]. In traditional applications they can provide a means for utilizing solar energy for domestic hot water or space heating, air conditioning, thermal driven cooling and industrial process heating applications. The main advantage of evacuated tube solar collector is to use it with an air cooler [6].

The prominent objective of this study is to enhance the performance of a general purpose air cooler when combining with a vacuum tube solar collector that is installed after the compressor. Solar air cooler is perhaps the most powerful development in solar vacuum tube technology. The solar thermal energy is collected in a device called solar collector. It consists of a dark coated surface called absorber, fluid flowing header contained in manifold and suitable protections for heat loss reduction, generally vacuum in this case. When exposed to the sun, the absorber absorbs the solar radiation and transfer a part of it to the fluid flowing through it. Vacuum tube collectors provide high temperature difference than the general flat plate solar collector and thus help to make it efficient solar air cooler systems.

2. Concept of a hybrid solar air cooler system

A single-stage vapor compression solar air-cooler consists of six major components, namely a compressor, a condenser, an expansion device, an evaporator, a solar vacuum collector and a solar storage tank. Fig.1 shows schematic block diagram of a solar air cooler system. The cycle starts with a mixture of liquid and vapor refrigerant entering the evaporator. The heat from warmed fluid collected from the solar collector is absorbed by the evaporator coil. During this process, the state of the refrigerant is changed from a liquid to a gas and becomes superheated at the evaporator exit. The superheated vapor then enters the compressor where a rising pressure will in turn increase the temperature. A vacuum solar panel installed after the compressor, uses solar radiations as a heat source to warm up the water. An insulated water storage tank is connected to the vacuum solar collector to maintain the water temperature. Therefore, the vacuum solar collector reheats the refrigerant to reach the necessary superheat temperature in order to reduce the required electrical energy to run the compressor. A valve is installed after the compressor to regulate the refrigerant mass flow rate. The refrigerant from the compressor goes through the copper coil inside the tank where a heat exchange is undertaken. From the storage tank the refrigerant then passes through the condenser and turns into liquid by rejecting latent heat.The liquid refrigerant then passes through capillary tube or expansion valve and its pressure and temperature is reduced and the refrigerant then enters ito the evaporator for repeating the cycle [7].

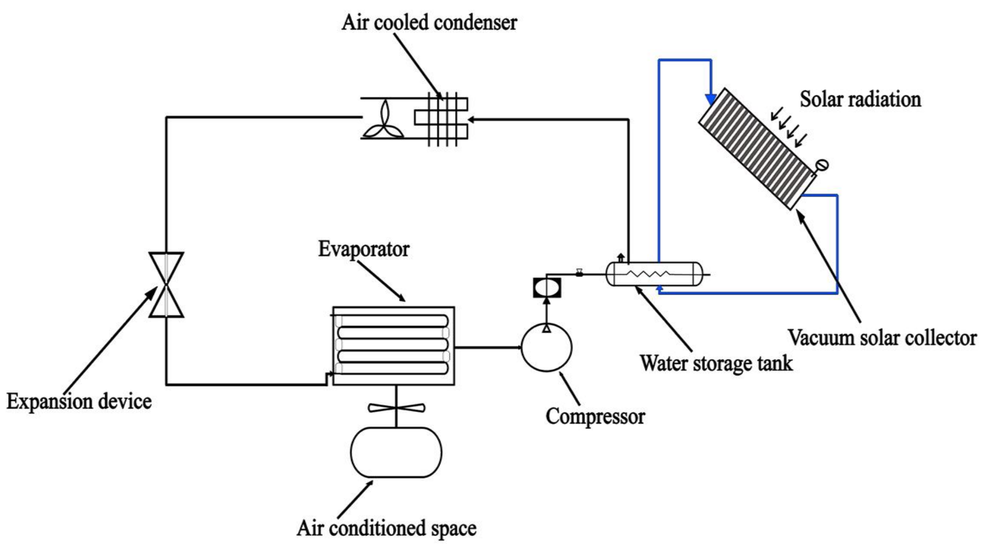


Fig. 1. Schematic block diagram of a solar air cooler system

3. Experimental setup

A vacuum tube solar collector consists of four main components**.** They are evacuated tube, heat pipe and copper header with manifold. Evacuated tubes are generally U shaped. A black paint coated copper tube heat pipe was used which was surrounded with a U shaped evacuated glass tube to vacuum it as required. For greater thermal efficiency low emissivity borosilicate glass tubes are used and black paint on the tube was used to enhance the solar energy absorption capacity [8]. The copper header pipe was situated in the insulated box called manifold. An aluminum casing was used to make a manifold. To reduce total roof loading in larger installation and for ease of installation, light weight of the manifold is important. In order to withstand the temperature of up to 482^{0}F the manifold was packed with glass wool insulation and is sealed with silicone rubber. An evacuated tube is shown in Fig. 2.

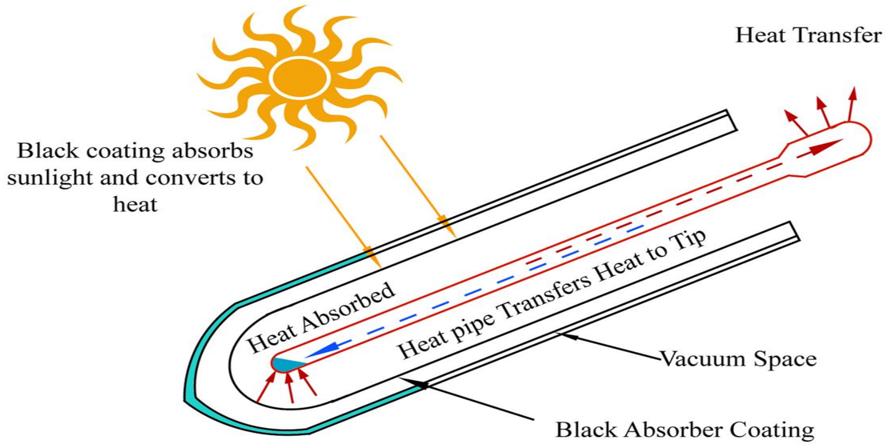


Fig. 2. Evacuated tube

Selection of working fluid is directly related to the properties of the working fluid. The properties are going to affect both the ability to transfer heat and the comparability with the case [9]. Table 1 represents some important properties of different working fluid which is commonly used in an evacuated tube collector [10].

Table 1. Properties of commonly used working fluid in a evacuated tube solar collector

Working Fluid	Melting Point, K at 1 atm	Boiling Point, K at 1 atm	Useful Range, K	Compatible Material
Freon 22	113.1	232.2	193-297	Aluminum
Freon 21	138.1	282.0	233-360	Aluminum, Iron
Freon 11	162.1	296.8	233-393	Aluminum
Freon 113	236.5	320.8	263-373	Aluminum
Acetone	180.0	329.4	273-393	Steel, Copper, Brass, Silica
Methanol	175.1	337.8	283-403	Copper, Brass, Silica, Nickel
Water	273.1	373.1	303-550	Stainless steel, Copper, Silica, Nickel, Titanium

Considering the favorable boiling and freezing point compatibility with the designed heat pipe material and availability, methanol was primarily chosen for the current solar collector. Table 2 shows physical properties of pure methanol [11].

Table 2. Physical properties of pure methanol

Properties	Value
Boiling Point (101.3 kPa)	337.75 K
Freezing Point	175.55 K
Latent heat of vaporization at	
298.15 K	37.43 kJ mol^{-1}
337.75 K	35.21 kJ mol^{-1}

The various components of the current solar collector with the dimensions were presented in Fig. 3. For the construction of a hybrid evacuated tube solar collector, four glass tubes were used with a center drilled hole on the top glass cover. In a folded 0.375″ copper pipe, methanol was injected which was used as the working fluid. Then four holes were drilled on the 1″ copper header pipe. A 0.5″ copper pipe as condensing unit was connected between the heat pipe and the header manifold. Vacuum pump and pressure gauge was used for making vacuum within the copper tube. -24 kPa vacuum pressures were maintained inside the heat pipe. Performance test of the solar collector was carried out placing the solar collector in a sunny place where average solar intensity 1000 W/m^2. Then, water was supplied through one end of the header in order to have the temperature difference for calculating solar collector's efficiency. The inlet and outlet temperature of the water was measured using a proper ranged thermometer. Mass flow rate was measured using a 100 ml measuring cylinder. The outlet water temeprature was recorded after half an our interval during the whole experimental interval of a sun shine day. Temperarue was recorded changing the mass flow rate at different interval of a definite sun shine day. Fig. 4(a) and 4(b) shows the schematic of the experimental solar collector setup and the photograph of the solar collector's construction respectively.

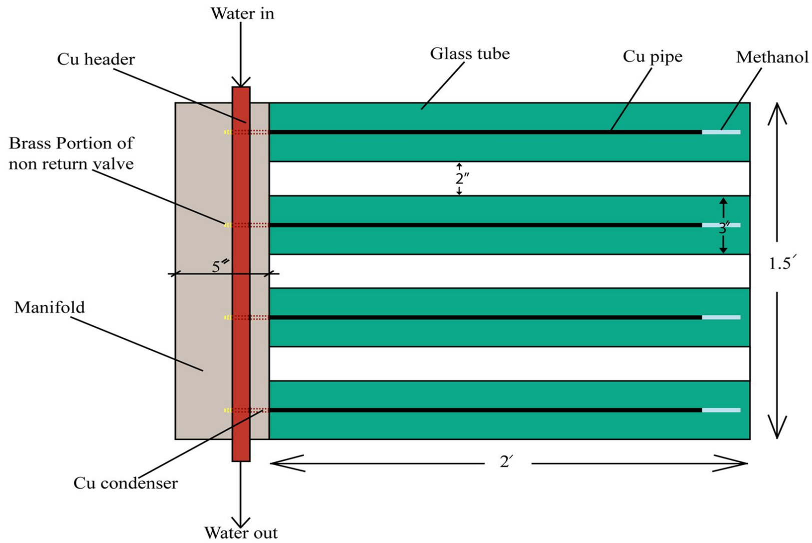
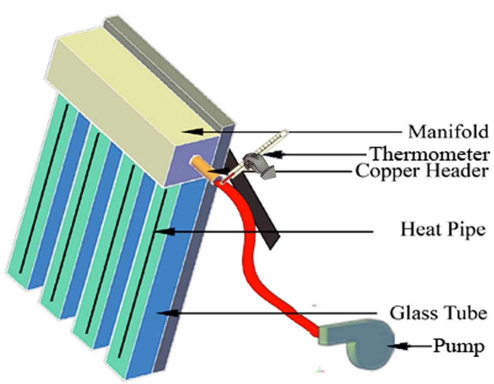


Fig. 3. Design of the hybrid evacuated tube solar collector



(a)

(b)

Fig. 4. (a) Schematic of the experimental solar collector setup (b) Photograph of the constructed solar collector

4. Results and Discussions

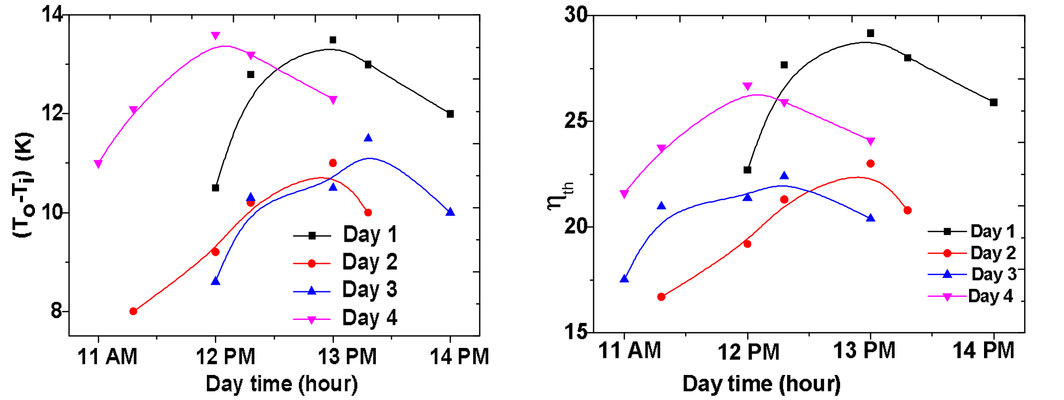
Solar intensity and mass flow rate of water are the two important factors upon which the efficiency of a solar collector depends on. Hence, experimental analysis was carried out by varying the mass flow rate of water in the range of 0.00189 -0.00208 kg/s and at different sun shine hour. Fig. 5(a) and 5(b) represents the temperature and efficiency variation of the collector with day time. In Fig. 5(a) it is seen that the temperature difference increases with time up to 1.30 PM and after that it decreases. At day 4, the minimum and maximum temperature difference was 11K at 11.00 AM and 13.6K at 12PM respectively for the mass flow rate of 0.0189 kg/s. It is seen that all the curves are parabolic in nature. The reason of parabolic shape is the increase of sunshine intensity till 1.30PM and its simultaneous decrease after the period 1.30PM.

The thermal efficiency of a solar receiver is another important parameter in evaluating its performance, which is defined as the ratio of the heat carried out by the working medium over the incident solar power. It is expressed as follows:

$$\eta_{th} = \frac{\dot{m} c_p (T_o - T_i)}{Q_{solar}}. \qquad (1)$$

Here, c_p is the specific heat of the heat transfer medium, T_i and T_o indicate the inlet and outlet temperature, $\dot{m}$ is the total mass flow rate of the working medium i.e. air for this analysis and Q_{solar} is the input solar power through the quartz window aperture of the receiver. Variation of the thermal efficiency (Fig. 5(b)) of the collector was shown the similar tendency like the temperature variation with day time. This intermittent nature is a problem for solar energy. Hence, a storage system can be added to solve the problem of constant power supply to the cooling system throughout the day.

Fig. 6 shows that, the outlet water temperature reduces with an increase in the water flow rate. The temperature of the outlet air was 13.6K higher at a mass flow rate of 0.00189kg/s and that was 13.5K for 0.00208kg/sec (Fig. 6). The reason behind this phenomenon was the increase of water temperature with the expense of absorbed solar energy by the collector. As the mass flow rate increases, large amount of water flows through the header and so more heat is taken away by the water. As a result the temperature was decreased with increasing the mass flow rate of water.



(a) **(b)**

Fig. 5. (a) Variation of temeprature difference (T_o-T_i) between the inlet and outlet air with the day time (b) Variation of thermal efficiency between the inlet and outlet air with the day time

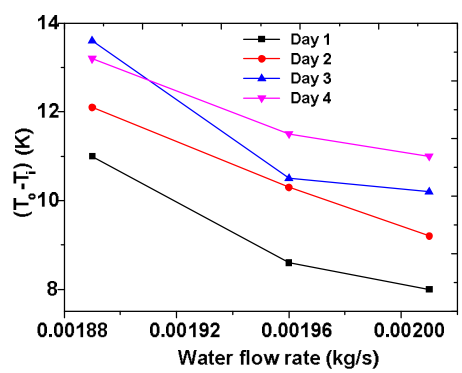


Fig. 6. Variation of temeprature difference (T_o-T_i) between the inlet and outlet air with the mass flow rate of water

5. Conclusion

In order to engage with an air cooling system, an evacuated tube solar collector is designed and constructed with an absorber area of 0.3675 m^2. In addition, the performance analysis was carried out through an experimental investigation. Experiments showed that the maximum and minimum outlet temperature difference was 10.5K at a mass flow rate 0.00189 kg/s and 13.5 K at a mass flow rate of 0.00208 kg/s a specific day. Also for a constant mass flow rate of 0.00189kg/s, the temperature difference increases at 13.6K at 12.00 PM and it was 11K at 11PM. The maximum obtained efficiency of the collector in this paper is 29.17% for mass the flow rate of 0.00208 Kg/s. The addition of this collector was able to reduce the power consumption of the evacuated compressor as the collector was added an additional 29% energy into the system. Hence, it helps to reduce the use of the conventional power in the system.

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