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Experimental Study of a Hybrid Evacuated Tube Solar Collector Using Methanol as Working Fluid

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Abstract— **Bangladesh is immensely dependent on conventional fuels to fulfill its energy demand, so these resources are depleting continuously. Renewable energy can be the alternative source to mitigate the increasing energy demand of this country. Among all renewable energies, solar energy is pollution free and available. Evacuated tube solar collectors are the most popular form of solar collectors because of its low coefficient of heat losses and high thermal efficiency. This paper deals with the design, fabrication and experimental investigation of a hybrid evacuated tube solar collector (ETSC). The constructed ETSC is attached to the air cooler, which helps to minimize the compressor power. ETSC consists of four borosilicate glass tubes and manifold. Each glass tube has a heat pipe and the heat pipe contains methanol as a heat transfer fluid inside it. A single pass header pipe is installed inside the manifold where water takes heat from the condenser. The experiments were conducted in the period of September to February in the climatic condition of Rajshahi, Bangladesh. The solar intensity varied in between 874 W/m2 to 984 W/m2. The results obtained from the experimental investigation showed that the thermal efficiency of the collector was 28.69% at a mass flow rate of 0.00188 kg/s. The collector energy is helpful to reduce the compressor power of the air cooler and results in an improved and efficient system.**

Index Terms— **Evacuated tube solar collector, Borosilicate glass tubes, Methanol.**

1. INTRODUCTION

Due to limited natural resources of this country, energy crisis is one of the exigent anxieties in Bangladesh. For the production of electricity, fossil fuels are ordinarily used as a form of energy. With increasing power generation and cost this limited natural resources are also reducing **[1]**. If alternative resources are not discovered, the reserved natural gas of Bangladesh will be diminished in the next 6-7 years. Again conventional resources of energy increase the pollution and amount of CO_2 in the environment. So, the prime need is the working of various governmental and nongovernmental organizations to make renewable resources an alternative source of energy **[2-5]**.

The most abundant and widespread source of renewable energy on earth is solar energy. This energy can be utilized efficiently in bridging up the gap between demand and supply of electricity. It doesn't produce any detrimental pollutants. In order to harvest and utilize solar energy properly researchers have investigated and developed various technologies. Solar air heaters, solar water heaters (SWH), solar drying, solar cooling technology etc. are some of the solar thermal technologies. Solar water heater uses thermosiphon principle to circulate water from the collector to the storage tank. This obtained hot water has many applications in domestic, commercial, and industrial sectors. The replacement of solar energy in place of electric energy or fossil fuels for water heating can reduce or even eliminate greenhouse gas emission. The two most common types of solar collector for solar thermal applications are Flat plate solar collector and Evacuated tube solar collector (ETSC). Among them ETSC is the most effective because of higher reliability and performance effectiveness than flat plate solar collector (FPSC) **[6-9]**.

The rise of ETSC has a momentous effect due to reduction in costs of the domestic SWH systems and lower heat loss than the standard FPSC. Conventional FPSC have reduced performance during cold, windy and cloudy days but ETSCs have outstanding thermal performance in adverse climates. Nalamwar G. C. et almentioned that at the same radiation intensity by comparing the heat gain of both the flat plate and vacuum tube solar collector having same capacity tank, mass flow rate and absorber area ETSC gives 16.12% higher efficiency than FPSC. ETSC performance is greatly improved by introducing a heat pipe in the collector tube as an absorbing element. ETSC has many applications like desalination of sea water, air conditioning, building heating, space heating, refrigeration, and industrial heating, instantaneous gas heater, boost element integrated single solar tank system, and boost tank incorporated solar pre-heaters **[10].**

The major objective of this study is to reduce the compressor power of the air cooler and hence the annual electric bill consumption. In this regard a borosilicate glass evacuated tube solar collector was constructed. Proper materials for different collector parts are selected to have better thermal efficiency of the collector.

2. EVACUATED TUBE SOLAR COLLECTOR

Heat pipe is called the heart of an ETSC. It has three main components namely evaporator, condenser and working fluid. It can be considered as an evaporating and condensing device for rapid heat transfer. The heat pipe involves an evaporating-condensing cycle for collecting heat. This heat helps to increase liquid up to its boiling point. A water based liquid in the heat pipe absorbs its latent heat of vaporization when sun rays fall on it. The liquid releases its latent heat of vaporization in the condenser when it comes into contact with the flowing liquid through the header. This process is repeated continuously as the evaporator is heated. Vacuum tube collectors provide high temperature difference than the general flat plate solar collector and thus help to make an

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efficient solar air cooler **[11]**. Fig. 1 shows the working principle of an evacuated tube.

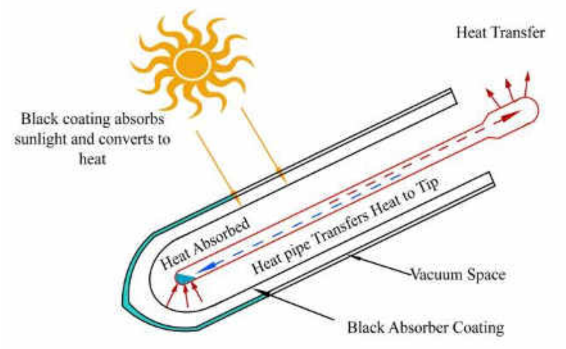


Fig.1. Working Principle of a Heat Pipe

Selective coating can suppress radiative and convective losses of an ETSC. These collectors normally have a smaller fraction of total occupied area actually intercepting solar radiation compared to 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 **[12]**. 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 **[13]**.

Many researchers have experimented on different types of heat pipes and revealed different heat transfer equations. In 2007, R. Singh et al. presented an experimental investigation on a copper miniature loop heat pipe (mLHP) with a flat disk shaped evaporator, designed for thermal control of computer microprocessors **[14]**. In 2010, R.A. Hossain et al.studied on the heat transfer phenomenon of a micro heat pipe **[15]**. They suggested the following equations. The thermal resistance, R (°C/W) is defined as,

$$R = \frac{T_e - T_c}{Q} \quad \text{................................(1)}$$

Where, T_e is the evaporator temperature, T_c is the condenser temperature and Q is the input heat. And the overall heat transfer coefficient, U (W/m^{20}C) is,

$$U = \frac{Q}{A_s(T_e - T_c)} \quad \text{...........................(2)}$$

Where, A_s is the surface Area.

In 2016, A. A. Ghoneima et al. analyzed the heat transfer characteristics of an evacuated tube. Data acquisition system was used to record solar radiation, temperature and flow rates instantaneously in that investigation. Useful energy was calculated using following Equation (3), given water flow rate and inlet and outlet temperatures of water **[11]**.

$$Q_u = \dot{m}C_p(T_o - T_i) \quad \text{.........................(3)}$$

In 2013, A. Kumar et al. experimented on the thermal performance of the glass evacuated tube solar air collector for producing hot air by estimating solar air collector efficiency which is defined as the ratio of output to the input **[16]**. Output in this case is the heat gain by air flowing through the manifold channel and input is the energy of the solar radiation falling on evacuated tubes:

$$\eta = \frac{Q_u}{AI} = \frac{\dot{m}C_p(T_o - T_i)}{AI} \quad \text{................................(4)}$$

Where, ṁ is the mass flow rate of air, C_p is the specific heat of the heat transfer medium, T_i and T_o indicate the inlet and outlet temperature, A is the area of the evacuated tube solar collector and I is the solar intensity.

3. WORKING FLUID

Selection of working fluid is directly connected to the respective thermo-physical properties of the working fluid. These properties are going to affect both the ability to transfer heat and the comparability with the case. The desire characteristics of a working fluid are good thermal stability, high latent heat, low liquid, vapor viscosities, high surface tension and acceptable freezing or pour point. Table 1 shows some of the commonly used working fluids, their suitable container material, melting and boiling points at atmospheric pressure, and their useful ranges **[17, 18]**.

Table 1. Working fluids their suitable container material and temperature ranges of heat pipes [17, 18]

Working Fluid	Container Material	Melting Point, °C	Boiling Point, °C	Useful Range, °C
Ammonia	Aluminum, Stainless Steel, Nickel, Carbon Steel, Iron	-78	-33	-60 to100
Acetone	Copper, Aluminum, Stainless Steel, Glass, Brass,	-95	57	0 to120
Methanol	Stainless Steel, Iron, Copper, Brass, Silica, Nickel	-98	64	10 to130
Ethanol	-	-159	78	0-130
Water	Stainless Steel, Copper, Silica, Nickel, Titanium	0	100	30 to 200
Mercury	Stainless Steel	-39	361	250 to 650

Considering the favorable boiling and melting point compatibility with the designed heat pipe material and availability, methanol was chosen for the current solar collector.

4. CONCEPT OF A HYBRID SOLAR AIR COOLING 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 the 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 liquid to 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 superheating 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 into the evaporator for repeating the cycle **[19]**.

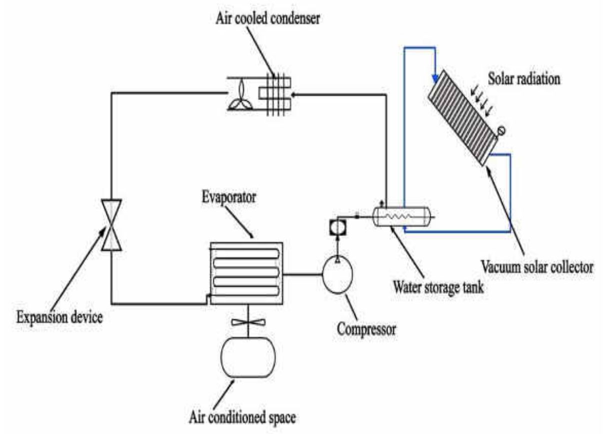


Fig. 2. Schematic block diagram of a solar air cooler system

5. METHODOLOGY

ETSC consists of four main components namely evacuated tube, heat pipe and copper header with manifold. Four borosilicate glass tubes were placed parallel to each other in the frame. Borosilicate glass tubes were used for greater thermal efficiency and low emissivity. The heat pipes were painted with black color to enhance the solar energy absorption capacity. The evaporator and the condenser portion of the heat pipe were made of 0.375 ″ and 0.5 ″ outside diameter copper pipe, respectively. Each heat pipe contained 9 ml of methanol. Vacuum pump was used to expel the inside air of the glass tube and heat pipe. The vacuum pressure inside the heat pipe was -24kPa. This vacuum pressure helps in lowering the boiling temperature of the working fluid. The copper header pipe was installed inside the manifold. A single pass header pipe of 1″ diameter was used as a common pipe where the working fluid dumped its heat. An aluminum casing was used to make the manifold. For ease of installation and light weight, aluminum was used to make the manifold. Manifold was insulated with glass wool and sealed with silicone rubber to withstand high temperature. The schematic diagram of an evacuated tube solar collector is shown in Fig. 2.

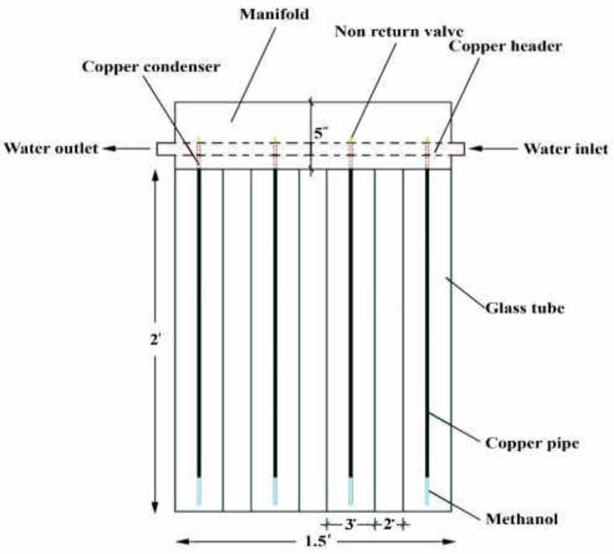
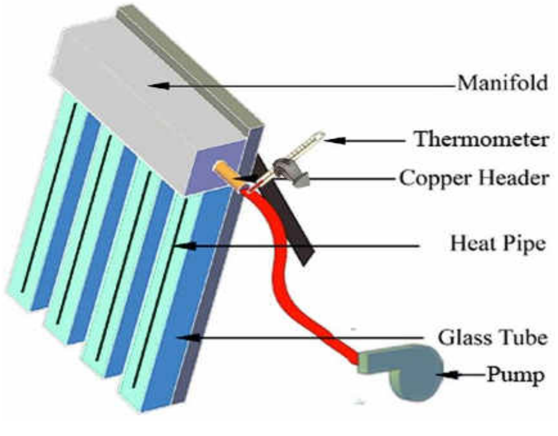
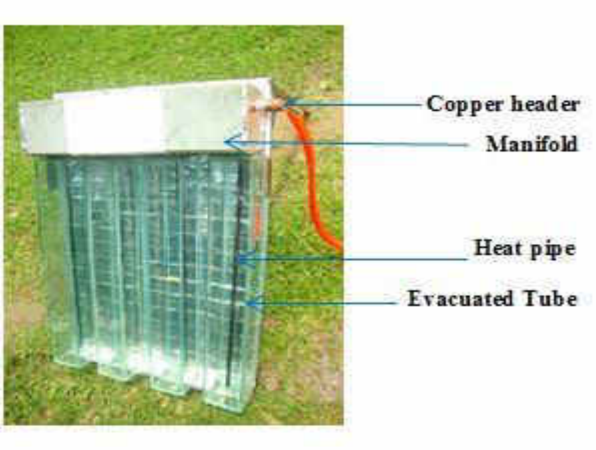


Fig. 3. Schematic diagram of an evacuated tube solar collector (Front view with dimensions)

When all parts were attached to the frame properly, the whole experimental setup was placed in a sunny place for performance test. In order to get the temperature difference, water was circulated through one end of the header for calculating solar collector’s efficiency. Water inlet and outlet temperature was measured using a proper ranged thermometer. Mass flow rate was measured using a 100 ml measuring cylinder. The outlet water temperature was recorded after half an hour interval. Temperature was recorded varying the mass flow rate at different interval of a definite sun shine day. K-type thermocouples assisted in measuring the evaporator and condenser section temperature. 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.



(a)Isometric view



(b) Photograph

Fig. 4. Whole experimental setup of an evacuated tube solar collector

6. Results and Discussions

The experiment was carried out in the months of September to February and with a varying mass flow rate of 1.32×10^{-3} to 2.3×10^{-3} kg/s at different solar intensity. The experiment was conducted from 10:00 am to 3:30 pm. The most important parameter for evaluating the performance of a solar collector is its thermal efficiency, which is defined as the ratio of the heat carried out by the working medium over the incident solar power. The efficiency of a solar collector depends largely on solar intensity and mass flow rate of circulating water through the header pipe. According to equation (4), the efficiency is inversely proportional to solar intensity and directly proportional to the achieved temperature difference. Fig. 5 represents calculated collector efficiency with respect to day time at various mass flow rates. It shows that the temperature difference increases with increasing solar intensity up to 12.30 pm and hence the efficiency also increases.The maximum outlet temperature and temperature difference are found at noon when the solar intensity is higher. When the solar intensity starts decreasing, the temperature difference also start decreasing. At higher solar intensity the collector efficiency has a lower value. The obtained maximum collector efficiency is 28.69% at 12:30 pm. The variation of solar intensity from September to February during the experimentation hours is shown in Fig. 6. The maximum solar intensity is 984 W/m^2 at 12:30 pm. From 10.00 am to 12.30 pm and 12.30pm to 3.30pm the solar intensity varied between 921 W/m^2 to 984 W/m^2 and 874 W/m^2 to 980 W/m^2 respectively.

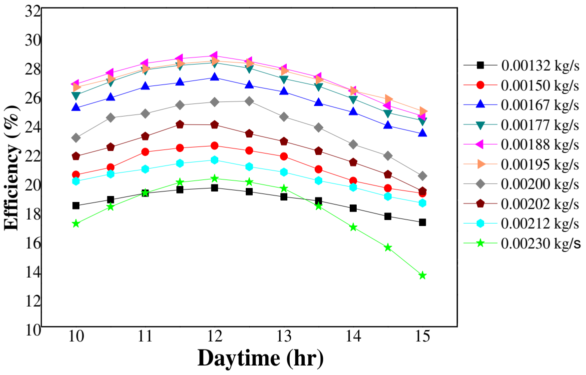


Fig. 5. Efficiency vs. Daytime curve for different mass flow rate

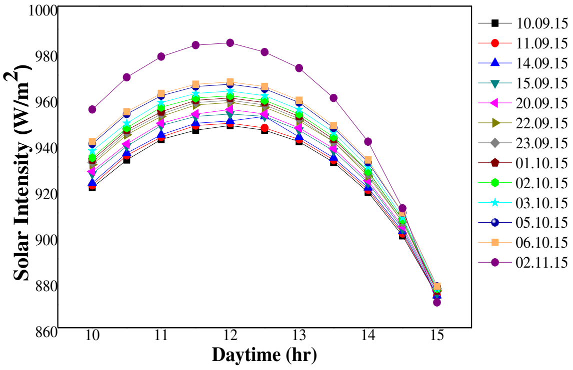


Fig. 6. Solar intensity vs. Daytime curve

Change in thermal efficiency of the collector with the variation of mass flow rate is demonstrated in Fig. 7. The figure says that the efficiency increases with mass flow rate up to an optimal value of 1.88×10^{-3} kg/s, where thermal efficiency reaches its highest maximum value of 28.69%. Then, for higher mass flow rates efficiency starts to decrease.This is due to the reduction in residence time of water for heat transfer inside the evacuated tubes collector. For low mass flow rates, the collector operates at a higher temperature, causing an increase in heat loss. Again, larger mass flow rates result in unstable outlet temperatures which also lead to an increase in heat loss. Hence the significance of determining the optimal flow rate is a very important factor in collector design. Fig. 8 shows the efficiency of the collector for the variation of $(T_i - T_a)/I$ from the value of 0.003 to 0.0055 m^{2o}C/W. At higher value of $(T_i - T_a)/I$, the collector efficiency has a lower value and at lower value of $(T_i - T_a)/I$ vice versa.

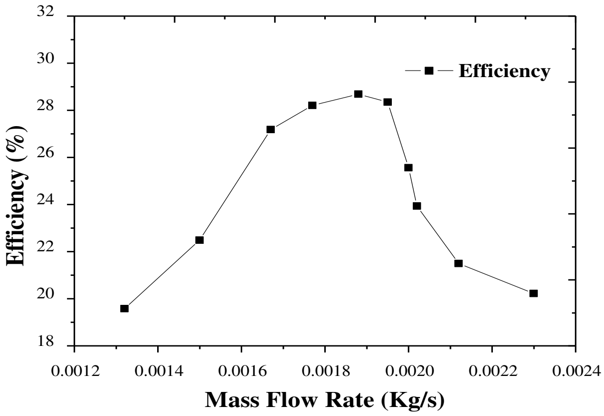


Fig. 7. Efficiency vs. Mass flow rate curve

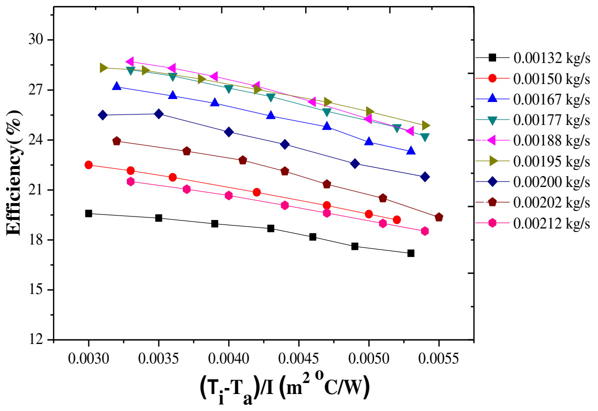


Fig. 8. Efficiency vs. $(T_i-T_a)/I$ curve

The outlet temperature and temperature difference of evacuated tube collector depend upon solar intensity and water flow rate. Fig. 9 represents the variation of outlet temperature with respect to day time. A maximum outlet temperature and temperature difference of air are 48.7^{o}C and 13.6^{o}C at 12:30 pm. When the solar intensity starts decreasing then outlet temperature also start decreasing. The outlet temperature rises up to 12.30 pm and after that it starts decreasing so it has a curve of parabolic nature.

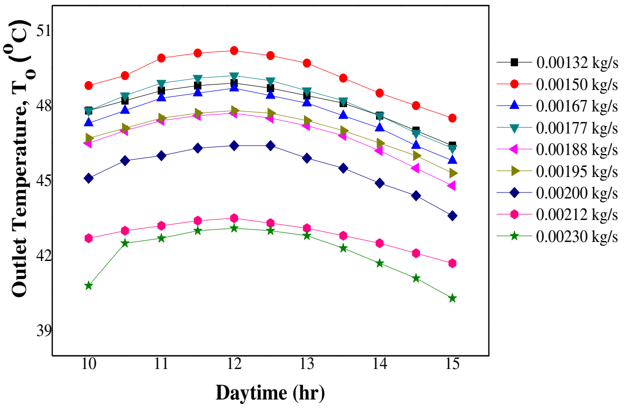


Fig. 9. Outlet temperature vs. Daytime curve

The variation of outlet temperature with respect to heat input is plotted in Fig.10. From figure it is found that, the outlet temperature and heat input has a proportional relationship. When the heat input increases, the overall thermal capacity of the system also increases hence the outlet temperature of the water increases. The maximum outlet temperature is 50.2^{o}C when the heat input is 350.96W. Heat output versus heat input curve is plotted in Fig.11. As heat input increases, heat output also increases. This curve also follows the similar trend as the previous one. The maximum heat output is 101.86W when the heat input is 355.01W.

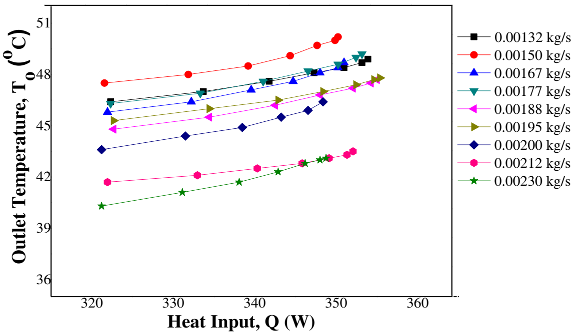


Fig. 10. Outlet temperature vs. Heat input curve

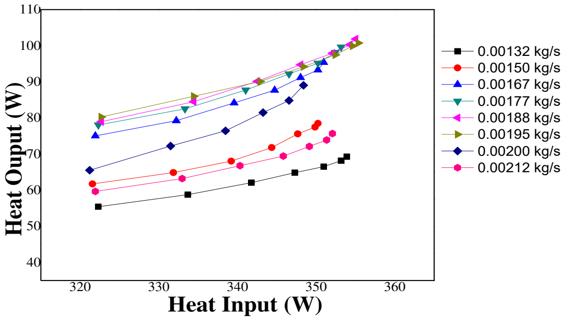


Fig. 11. Heat output vs. heat input curve

Variation in thermal resistance with the heat inputs is shown in Fig.12. The thermal resistance of heat pipe depends on heat input and temperature difference between evaporator and condenser. According to equation (1), the thermal resistance of heat pipe can be calculated from the ratio of the temperature difference between evaporator and condenser section to the power supplied. It is seen that the thermal resistance of the system decreases with increase in heat input due to the chaotic fluid movement. Ultimately the temperature difference between evaporator and condenser decreases.The experiments are carried out for input heat fluxes ranging from 320.09W to 355.37W.When the heat input is higher that is 355.37 W, the minimum value of thermal resistance is obtained (0.028 ^{o}C/W).

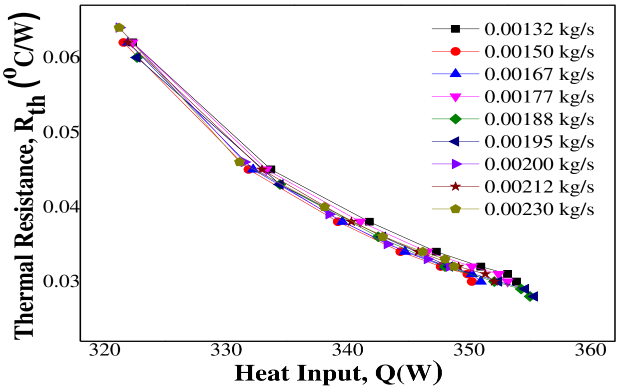


Fig. 12. Thermal resistance vs. heat input curve

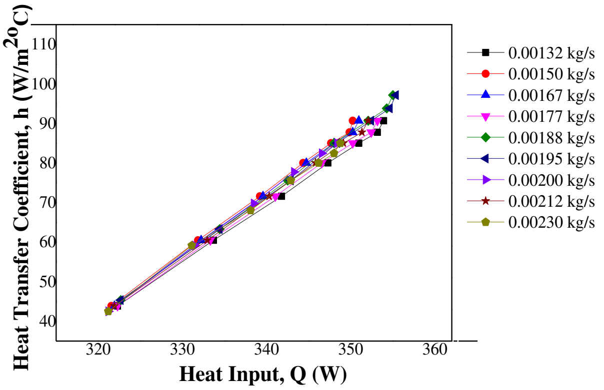


Fig. 13. Heat transfer coefficient vs. heat input curve

Variation in overall heat transfer coefficient with varying heat input is shown in Fig. 13. The heat transfer coefficient of heat pipe depends on heat input, surface area of evaporator section and temperature difference between evaporator and condenser.The overall heat transfer coefficient can be calculated using equation (2). From figure it is found that, as resistance of heat pipe increases the overall heat transfer coefficient decreases and as thermal resistance of heat pipe decreases the overall heat transfer coefficient increases. With the increase in heat input, the heat transfer coefficient increases and with the decrease in heat input it decreases. The maximum value of heat transfer coefficient is 97.18 W/m^{2o}C for the heat input of 355.37W.

CONCLUSIONS

Based on the findings of the current work, following conclusions were extracted:

- An evacuated tube solar collector is designed with an area of $0.3675\ m^2$.
- The optimal mass flow rate is 1.88×10^{-3}kg/s, when the collector efficiency achieves its highest maximum value of 28.69 %.
- The maximum solar intensity is 984 W/m^2 at 12:30 pm.
- Experiments show that the maximum outlet temperature difference is 13.6°C when the mass flow rate is 1.67×10^{-3}kg/s.
- The maximum outlet temperature is achieved 50.2 °C at a mass flow rate of 1.50×10^{-3}kg/s and heat input of 350.96W.
- The heat transfer coefficient increases with the increase in heat input. Thermal resistance decreases as heat input increases.
- The collector is able to transfer maximum heat load of 355.37 W.
- The minimum value of thermal resistance is 0.028°C/W at 355.37 W heat input.
- The maximum value of overall heat transfer coefficient is 97.18 $W/m^{2o}C$ at 355.37W heat input.
- The maximum heat output is 101.86W when the heat input is 355.01W.

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