Experimental Investigation of Solar Steam Generator Based on Evacuated Tube for Heating and Humidification

Sajith Lawrance, Anunaya Saraswat and Avadhesh Yadav

Abstract In this paper, experimental investigation of solar steam generator based on evacuated tube for heating and humidification has been carried out. The experimental setup consisting of 40 evacuated tubes, a header, and a duct. Water in the header is heated up and converted to steam by using solar energy collected by the evacuated tubes. Steam was generated for 3 h from 13:00 to 16:00 h. The generated steam from the collector is mixed with the ambient air flowing through the duct. The air-flow rate was fixed at 52.31 kg h^{-1}. The conditions at the outlet of the duct are recorded after every half an hour. The maximum temperature difference and humidification rate of 6 °C and 0.580 kg h^{-1} was obtained at 14:00 h, respectively. The results show great potential of evacuated tube collectors for winter air conditioning.

Keywords Solar air conditioning · Solar energy · Evacuated tube collector · Heating and humidification · Winter air conditioning

1 Introduction

The demand for electricity is increasing with rising population, industrialization, and modernization. Developing countries find themselves short in meeting this constantly increasing demand. Most of the power plants still use fossil fuels to produce electricity. These fossil fuels are at the verge of extinction; again burning of these fuels cause environmental problems like air pollution, soil pollution, etc. The above reasons are forcing us to find an alternative energy source, which is renewable and nonpolluting. Solar energy being the most potential and clean energy has attracted scientists through decades.

Evacuated tubes have vacuum around the absorber tube, which reduces convection heat loss thus they better performance than flat plate collectors particularly

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for high temperature application [1]. After the development of sputter coating machines used for applying selective coating on the absorber tube the market share of evacuated tube collector is rapidly growing.

Following are some of the studies carried out on evacuated tubes till date. A study was carried out to calculate the solar radiation received by cylindrical absorber inside evacuated tube [2]. A study was carried out to corelate the natural flow of fluid inside a single ended evacuated tube collector the result showed that the natural circulation could be corelated with collector inclination, solar intensity, tank temperature, and aspect ratio of the tube [1]. Morrison et al. [3] developed different heat extraction methods for evacuated tubes also numerically studied water circulation behavior in single ended evacuated tube. Evacuated glass tube was investigated numerically and experimentally. The results showed that the performance was related to shape of absorber, incidence angle of radiation and arrangement of tubes [4]. Thermal performance of evacuated tube is evaluated using energy equation also influence of air between copper and absorber tube on efficiency is studied [5]. Studied optimal tilt angle for different types of evacuated tubes and found that tilt angle has to be less than latitude angle [6]. A setup was fabricated for air heating with evacuated tubes; it was also integrated with phase change material [7].

Evacuated tube has been studied since. 1950s [8], still no work has been carried out to produce steam with evacuated tube collector, also no work has been reported on heating and humidification of air with ETC. Heating and humidification is necessary for applications like winter air conditioning, green house, etc. In this paper an experimental investigation of solar stem generator based on evacuated for heating and humidification is presented. The setup is installed at NIT Kurukshetra, Haryana, India (29° 58′ North and 76° 53′ East).

2 System Description

Solar steam generator based on evacuated tube for heating and humidification is shown in Fig. 1. The system consists of 40 evacuated tubes attached to a header. The high head of the header opens to the duct. A blower is attached to the duct as shown in figure. Evacuated tubes and header are inclined at 5° and 15° from the horizontal, respectively. The header and the forty evacuated tubes are filled with 80 L of water. Two photographic view of the setup is shown in Figs. 2 and 3. The main components of the system are as follows.

2.1 Evacuated Tubes

Evacuated tubes are made up of two coaxial borosilicate glass tubes fused at one end. The dimensions of the tubes are inner diameter 37 mm, outer diameter 47 mm

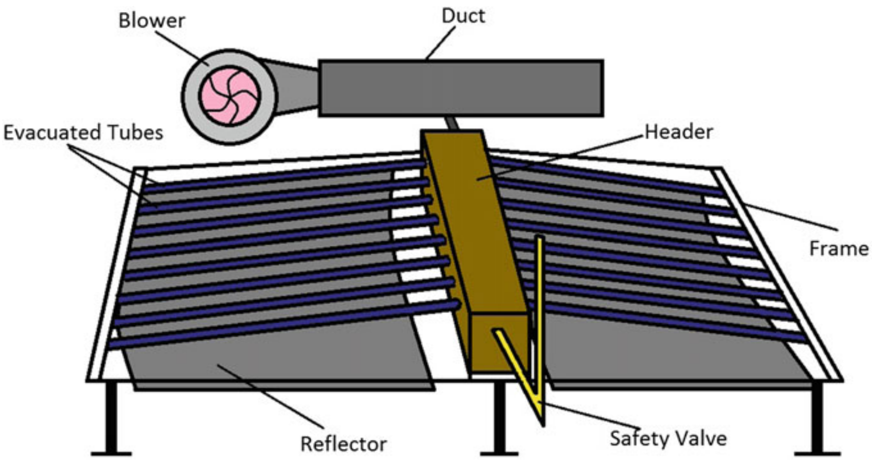

Fig. 1 Schematic diagram of the setup

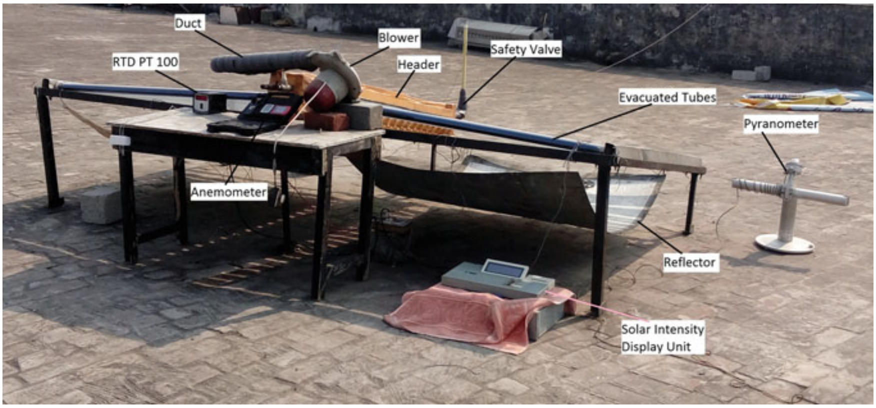

Fig. 2 Photograph of the setup (view 1)

and length 1500 mm each. There is vacuum between the two layers of the glass to reduce the heat transfer loss. The outer tube is transparent and has high transmissivity. The outer surface of the inner tube is coated with a layer of aluminum nitride (Al-N/Al) this coating has high absorptivity and less emissivity.

2.2 Header

Schematic diagram of the header is shown in Fig. 4. The header is fabricated from a steel box of dimension 120 mm × 120 mm × 1500 mm. This header is insulated

Fig. 3 Photograph of the setup (view 2)

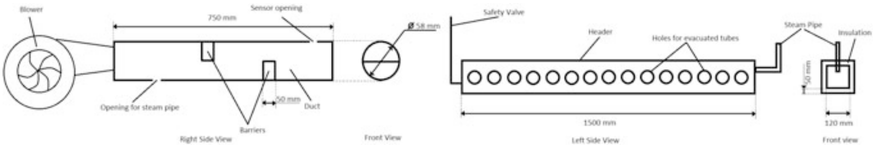

Fig. 4 Schematic diagram of the duct (*left*) and the header (*right*)

with polystyrene from all sides to decrease the heat loss. The thickness of the insulation is 50 mm. A safety valve is attached to the low head of the header. A pipe was provided at the high head of the header for steam outlet.

2.3 Duct

A newly designed duct is fabricated for this setup. The schematic diagram of the duct is shown in Fig. 4. It is made of polyvinyl chloride material. The duct has length of 750 mm and diameter of 58 mm. Blocks of polystyrene material is fixed inside the duct as shown in figure to ensure proper mixing of steam with the flowing air.

2.4 Reflector

There are gap between the evacuated tubes. Some part of the incident solar radiation get lost as these rays do not fall on the tubes and escape through the gap. In order to minimize this loss a reflector is attached under the tubes, which reflect the solar radiations back to the tubes. The reflector has dimension of 1550 mm × 1200 mm.

This reflector is made from galvanized aluminum sheet having zinc coating on the surface. It has reflectivity of 86%. The zinc coating helps in increasing the reflectivity of the sheet.

3 Measuring Devices and Instruments

In this experiment the data recorded were temperature of water at low head and high head of header, ambient dry bulb and wet bulb temperatures, duct outlet dry bulb and wet bulb temperatures and solar radiation. The air-flow rate was kept constant. The details of devices used for measurements are shown in Table 1.

4 System Working

The setup was exposed to the sun one day before the readings were taken. Natural circulation of water taking place in header and evacuated tubes are shown in Fig. 5. Water in the evacuated tubes is heated up by the energy received from the sun. Due to this heating and inclination of tubes, thermosyphon effect takes place in the tubes, thus hot water from pipes moves to the header and cold water from header rushes into the tubes. The inclination of the header with the horizontal plane forces

Table 1 Specification of measuring instruments

Measurement	Devices	Range	Accuracy
Solar intensity	Pyranometer	0–1400 W m^{-2}	±2 W m^{-2}
Temperature (dry bulb and wet bulb)	RTD PT 100 temperature sensor	0–200 °C	±0.3 °C
Air velocity	Anemometer	0–45 m s^{-1}	±2%

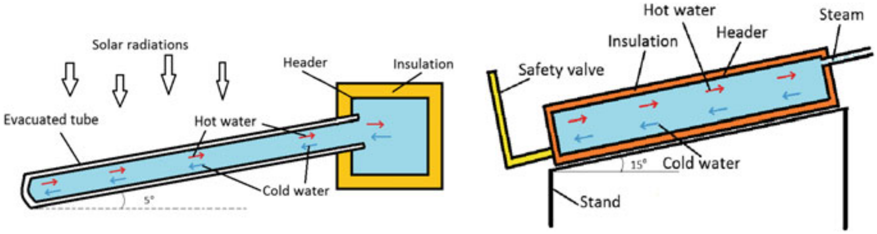

Fig. 5 Thermosyphon in evacuated tubes (*left*) and thermosyphon in the header (*right*)

hot and less dense water to the top of the header. The hot water at the high head of the header gets converted into steam. This steam is then carried into the duct by the steam pipe. The steam gets mixed with the air flowing in the duct thus heating and humidifying the air.

5 Performance Indexes

The performance of the system is measured in terms of its COP (coefficient of performance), which is the ratio of the energy gained by the air to the solar energy received for that duration dt (in seconds). Where m_a is mass of air, h_1 is enthalpy of ambient air, h_2 is enthalpy of air at outlet of duct, I is solar intensity, and A denotes collector area. An example calculation follows. The input and output of the system is calculated for every half an hour and added up to calculate the overall COP of the system for that day, for, e.g., the enthalpy of air at inlet and outlet of the duct at 13:00 h were 44.937 and 56.457 kJ kg^{-1}, respectively, and at 13:30 h were 46.392 and 72.33 kJ kg^{-1}, respectively. The average enthalpy difference came out to be 18.729 kJ kg^{-1} for this half hour period. The air-flow rate was constant at 52.31 kg h^{-1}. The average solar intensity for this period was 720.5 W m^{-2} and the area of collector was 4.44 m^2

$$\mathrm{COP} = (m_a 1000(h_2 - h_1)) \div (IA\mathrm{d}t). \quad (1)$$

6 Results and Discussion

The experiment was carried out at NIT Kurukshetra, India on 6th of February 2016. There was fog till 10:00 in the morning after which the sky was clear. The data were recorded from 10:30 to 16:00. Ambient temperature varied from 8 to 25 °C. The air velocity was fixed at 5.5 m s^{-1}. The steam started generating at 13:00 and was generated for 3 h till 16:00.

Variation of temperature of water at low head (L.H.) and high head (H.H.) of the header with solar intensity and time is shown in Fig. 6. The temperature at the high head increased continuously with time till it reached 101 °C, it almost remained constant after that. This temperature increased continuously even when the solar intensity was decreasing; this is because of the following reasons, the system works as a closed system as no feed water is added to the setup thus the temperature of water will increase till there is more input than output. The setup generates output only after reaching temperature above 100 °C, hence, there is no output at this point and solar energy is delivering input, which is decreasing but still there is input. Thus increasing the high head water temperature. But due to decrease in solar intensity the rate of increase in temperature of water decreased. After the water

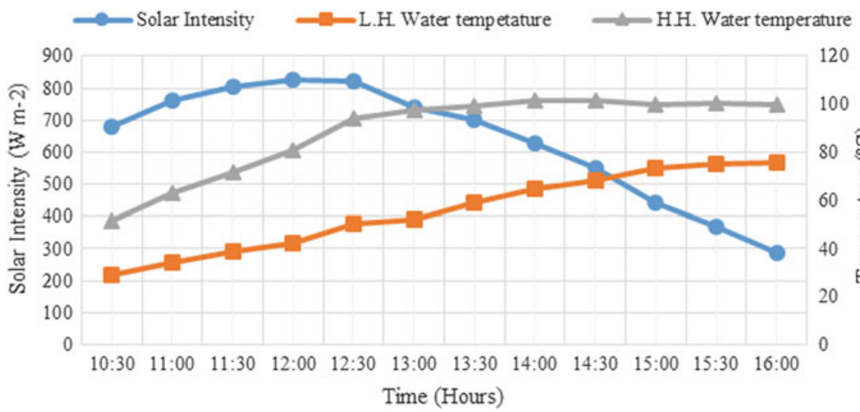

Fig. 6 Variation of water temperature and solar intensity with time

attained temperature of 101 °C the setup started delivering output and thus the temperature of water remained constant. The low head showed almost same curve like the high head the exception was it gained heat by conduction from high head when the solar intensity was diminishing. It reached a maximum temperature of 75.7 °C. The solar intensity reached a maximum value of 827 W m^{-2} at 12:00 h.

The condition of air at outlet of duct and ambient condition of air in terms of its humidity and temperature is shown in Fig. 7. The ambient air temperature (dry bulb temperature) remained between 23.4 and 24.6 °C during the working hours (working hours of setup). The setup was able to maintain the outlet temperature between 30 and 27.4 °C. The ambient air humidity stayed between 8.40 and 9.50 g kg^{-1} during working hours. The setup was able to maintain the outlet humidity between 9.50 and 19.6 g kg^{-1}. The curve of outlet humidity ratio was related to high head water temperature and solar intensity. Initially with rise in temperature of high head water the humidification rate increased but latter on with the considerable drop in solar intensity the humidity at outlet also dropped.

Figure 8 shows the temperature (dry bulb temperature) difference obtained for air at the outlet of duct to ambient air, and the humidification rate achieved by the setup. The temperature difference obtained can be associated with high head temp and solar intensity. Initially when the high head temperature was increasing the temperature difference kept on increasing but with the considerable fall in solar intensity the temp difference started decreasing. At 15:30 the temperature suddenly raised instead of decreasing this was because of sudden fall in ambient temperature of air, which created large difference in temperature of setup water and incoming air, increasing the heat transfer coefficient. The maximum temperature difference obtained was 6 °C at 14:00. The humidification rate obtained can be associated with high head temp and solar intensity. Initially when the high head temperature was increasing humidification rate kept on increasing but with the considerable fall in solar intensity the humidification rate started decreasing. The maximum humidification rate of 0.580 kg h^{-1} was achieved at 14:00 h.

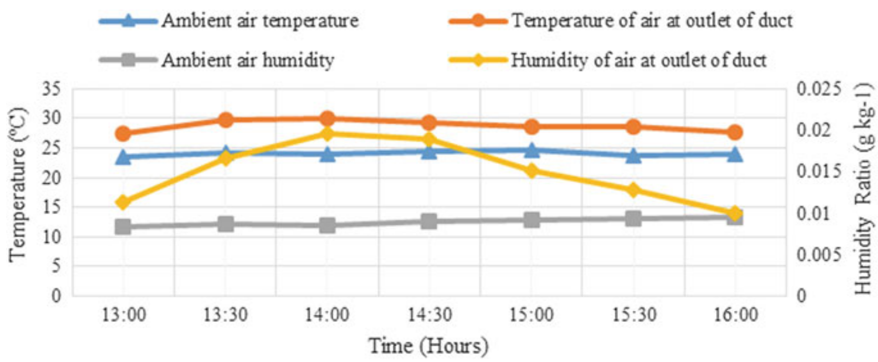

Fig. 7 Variation of temperature and humidity ratio with time at inlet and outlet of the duct

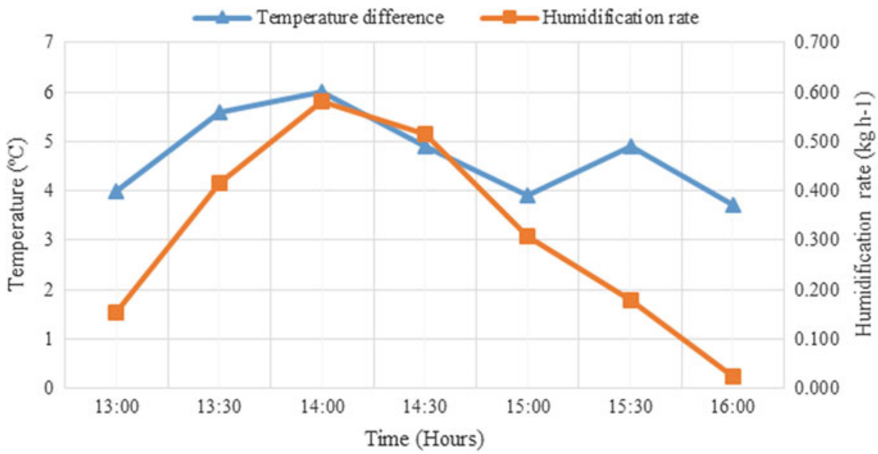

Fig. 8 Variation of temperature difference, humidification rate with time

The COP of the system is calculated using Eq. (1) shown in performance indexes. The overall COP obtained by the setup was 0.0599. Though the COP seems little on the lower side there is another output, i.e., hot water that is not considered in the calculation of COP. Thus the overall efficiency of the system can be improved if we can make use of this hot water.

7 Conclusions and Recommendations

On a typical north Indian winter conditions where ambient temperature varied from 8 to 25 °C the setup was able to maintain a temperature difference of 3.5–6 °C for 3 h. The maximum humidification rate obtained was 0.580 kg h^{-1}. The setup obtained overall COP of 0.0599. The above results show that the steam generator based on evacuated tube has great potential for replacing winter air conditioners but further research need to be done in this field. Some of the future work that can be done is integrating this system with phase change material or other thermal storage system, automatic controlling of the steam and controlling of air-flow rate with sensors.

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