An Experimental Study on Evacuated Tube Solar Collector for Steam Generation in India

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Abstract**—**An evacuated tube solar collector is experimentally studied for steam generation. When the solar radiation falls on evacuated tubes, this energy is absorbed by the tubes and transferred to water with natural conduction and convection. A natural circulation of water occurs due to the inclination in tubes and header. In this experimental study, the efficiency of collector has been calculated. The result shows that the collector attains the maximum efficiency of 46.26% during 14:00 to 15:00h. Steam has been generated for two hours from 13:30 to 15:30 h on a winter day. Maximum solar intensity and maximum ambient temperatures are 795W/m^2 and 19^{o}C respectively on this day.

Keywords**—**Evacuated tube, solar collector, hot water, steam generation.

I. Introduction

In present scenario, world is having a crucial situation of energy shortage. Non-renewable sources of energy viz. coal, gas, crude oil etc. are depleting continuously. Use of these source causes environmental harm such as depletion of ozone layer, acid rain, global warming etc., which is also harmful to human life. Some fraction of these sources is also utilized in the production of steam. Therefore, it is necessary to find an alternative way to produce steam, which should be eco-friendly and based on renewable source. In this context, solar energy is the most available source, which can be utilized by using evacuated tube solar collector (ETC) for steam generation. The number of literature has been studied based on evacuated tube collector. Amongst them few literatures suggested a development of a radiation model for evacuated collector with tubular absorber [1]. The tube geometry and design of panel for evacuated tube solar collector was investigated [2]. A geometrical method was developed to determine the size of each tube and position of shadow of each tube to its adjacent tube [3]. A collector with parallel–connected evacuated glass tubes was investigated experimentally and they theoretically studied about the solar azimuth angle, distance between the tubes and expected yearly thermal performance of collector for different climates [4]. The performance of the water in evacuated tube act as a solar water heater was measured [5]. The characteristics of water in evacuated tube with circulation rate through single ended tubes had been evaluated [6]. The thermal performance of evacuated tube collector has been investigated experimentally [7]. An experimental setup was established to obtain optical and heat transfer characteristics. The performance of single ended evacuate tube was investigated based on simulation model of natural circulation in tubes [8]. Using analytical method thermal performance of each evacuated tube in the setup was investigated [9]. The performance of water-in-glass evacuated tube solar water heater (SWH) was analyzed at two different angles (22^o and 46^o) from horizontal surface. The experimental investigation showed that both systems had same solar thermal efficiency, but different daily heat gains. They concluded that heat gain can be maximized at optimized tilt angle [10]. They analyzed the comparative performance of direct flow co-axial evacuated tube solar collectors with and without heat shield. It was resulted that evacuated tube solar collector with heat shield performed better than solar collector without heat shield. They also concluded that solar collector with heat shield had collector efficiency of 54.7% at highest inlet temperature of 123.9^{o}C, whereas the solar collector without heat shield had collector efficiency of 23.21% [11]. A mathematical model was modified and developed to evaluate the performance of water in evacuated tube collector. The results in Egypt (30^o Latitude angle) showed that the optimum solar collector tilt angles are 10^o, 30^o and 45^o for the summer, vernal and autumnal equinox and winter operation respectively. They also showed that per tube can absorb maximum 80W of solar radiation [12]. They reviewed the progress and latest developments of evacuated tube solar collectors. Different applications of evacuated tube collector in heat engines, water heating, swimming pool heating, air conditioning, steam generation, solar cooker, and solar drying for industrial and residential sectors and had been summarized [13].

The objective of this article is to investigate the performance of evacuated tube solar collector for generation of low pressure steam in winter season in Northern Indian climatic condition.

II. Experimental Setup

The motive of the experiment is to study the performance of evacuated tube solar collector for steam generation. This system has forty evacuated tubes with header, arranged as shown in Figs. 1 and 2. A safety valve is attached to header for safety purpose. Reflectors are placed below the evacuated tubes to increase the performance of the setup. A volumetric cylinder is attached at high head of header through a pipe and it is used to collect the generated steam.

There are two major parts in the setup i.e. evacuated tubes and header. These parts of the setup are presented by the schematic diagram as shown in Fig. 1. A photograph of the

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setup is also shown in Fig. 2.

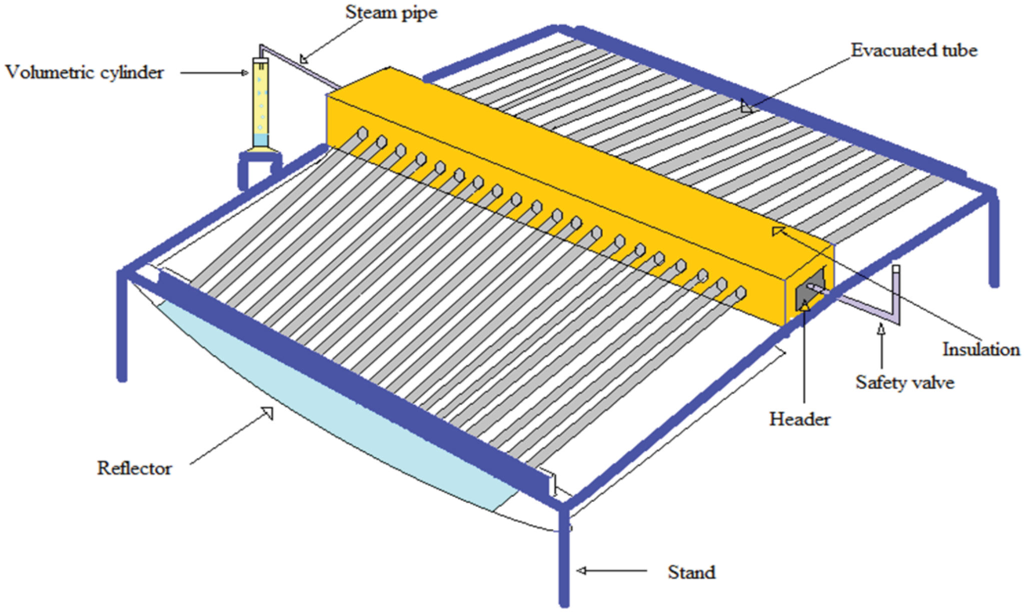

Fig. 1 A schematic diagram of evacuated tube collector for steam generation

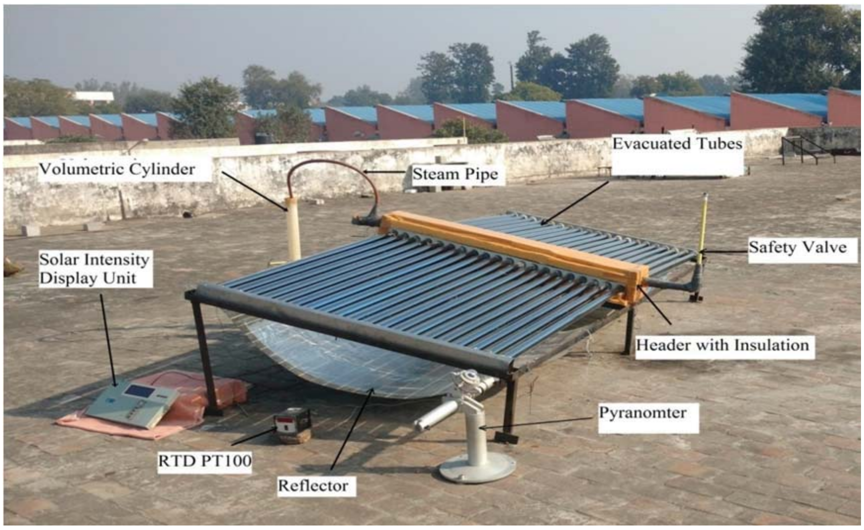

Fig. 2 A photograph of evacuated tube collector for steam generation

A. Evacuated Tubes

A schematic Diagram cross-section of evacuated tube is shown in Fig. 3. The evacuated tube has two concentric borosilicate glass tubes. There is a vacuum present between these glass tubes. The outer tube has high transmissivity and minimal reflectivity. The inner tube has a layer of selective material and this selective material has a high absorptance and low emittance property. The specifications of evacuated tubes are as shown in Table I.

TABLE I
SPECIFICATIONS OF EVACUATED TUBE

Parameters	Values/Properties
Length	1500mm
Outer diameter	47mm
Inner diameter	37mm
Material	Borosilicate glass
Selective material	Al-N/ Al
Absorptance	>92%
Emittance	<8% (80°C)
Vacuum	$P<5x10^{-3}$
Maximum strength	0.8MPa

B. Header

A header is designed and fabricated for the setup. A schematic diagram of the header is shown in Fig. 4. It has a square pipe with dimension of 120mm x 120mm. This square pipe is made up of steel. There are forty holes provided in this square pipe, 20 hole each side. Open ends of evacuated tubes are placed in these holes and closed ends are supported by a frame. An insulation of polystyrene is attached over the square pipe. The thickness of insulation is 50mm. This insulation conserves heat loss from header to surrounding. There is a pipe provided for steam outlet.

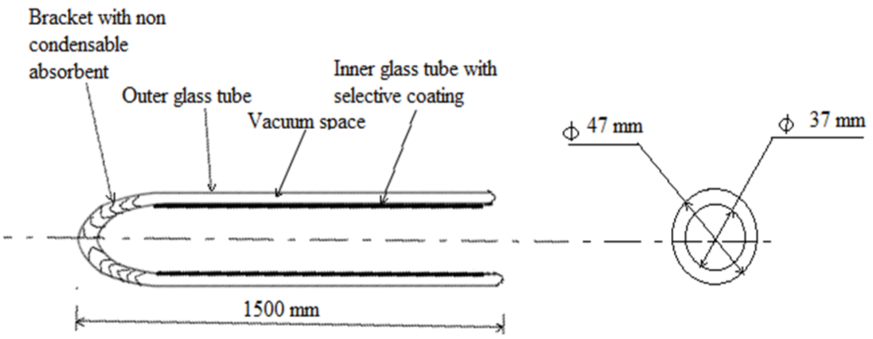

Fig. 3 A schematic diagram of cross-section of the evacuated tube

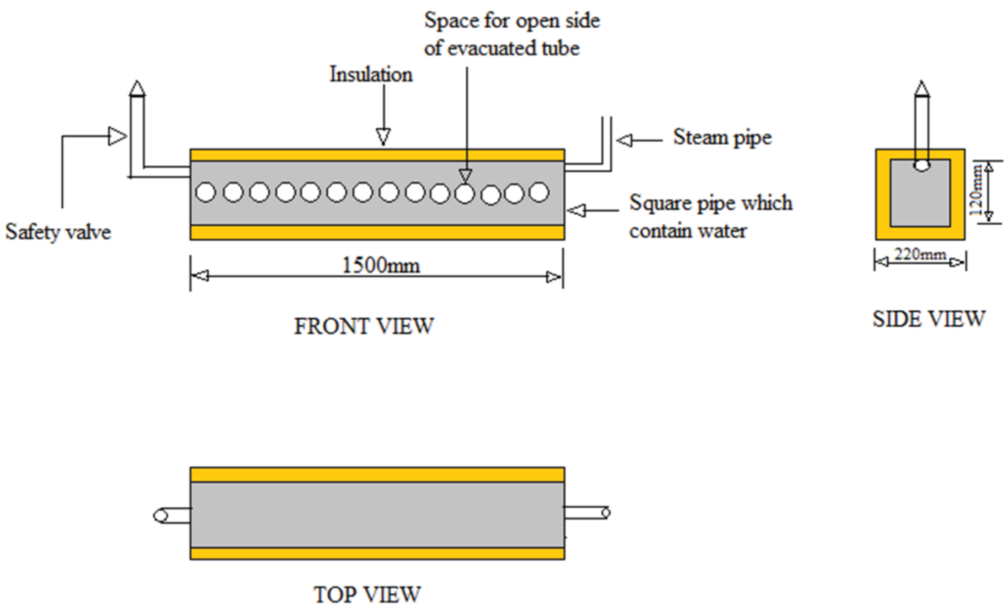

Fig. 4 A first angle projection of header

III. Measuring Devices and Instruments

In this study, different parameters at different points are measured.

- Temperature of water at low head and high head,
- Temperature of steam,
- Intensity of solar radiation,
- Quantity of steam.

The specifications of measuring instruments, which are used in experimental setup are shown in Table II.

IV. System Operation

The setup contains forty evacuated tubes and header. The setup is filled with 80 liters of water. When solar radiation falls on the evacuated tube, it is absorbed by evacuated tubes. This energy is then transferred to the water due to natural conduction and convection. In this setup, evacuate tubes are inclined at 5° from horizontal and header is inclined at 15° from horizontal. A natural circulation of water occurs due to the inclination of evacuated tubes and this water is delivered to header as shown in Fig. 5.

There are two heads i.e. low head and high head in the header due to inclination. Thermosyphon occurs due to a temperature difference between high head and low head. When water at the high head reaches to its boiling point it converts into steam. This steam comes out from steam pipe and is collected in the volumetric cylinder as shown in Fig. 6.

TABLE II
SPECIFICATION OF MEASURING INSTRUMENTS

Measurement	Device	Range	Accuracy
Temperature	PT100 RTD Temperature sensor	0°C to 200°C	± 0.3 °C
Quantity of steam	Volumetric cylinder	50ml to1000ml	± 10 ml at 20°C
Solar Intensity	Pyranometer	0 W/m^2 to 1400 W/m^2	± 2W/m^2

V. PERFORMANCE OF EVACUATE TUBE COLLECTOR

The thermal performance of evacuated tube solar collector is denoted by the factor of solar collector efficiency(η), which is the ratio of the net heat gain to the solar radiation energy based on the area of solar collector(A) [9]. The formula used to determine efficiency of evacuated tube solar collector is as (1). Here, dT denotes temperature difference and dt denotes duration of time.

$$\eta = \frac{(m_w C_p dT + m_v L_v + m_v C_{ps} dT)}{IAdt} \quad (1)$$

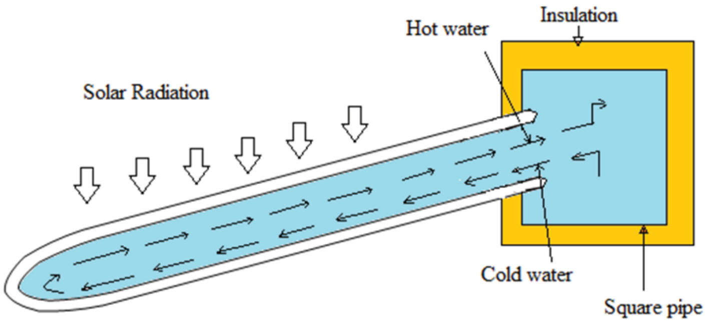

Fig. 5 Thermosyphon in evacuated tube

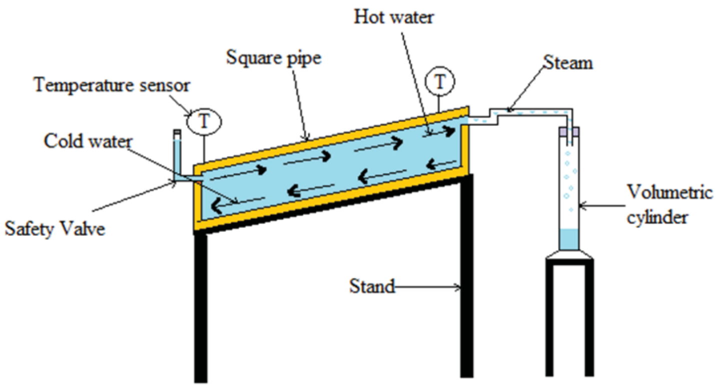

Fig. 6 Thermosyphon in header

VI. RESULTS AND DISCUSSION

In this setup, the main focus is to calculate the thermal performance of evacuated tube collector for steam generation in winter season in Northern Indian climatic condition. The data is collected at NIT Kurukshetra on 18/12/2015, which is a clear sky day. The experimental test was carried out from 10:00 to 16:30h. The ambient temperature varied from 8°C to 19°C during the test. The efficiency of collector is calculated using (1) as:

$$\eta_{9:00\text{-}10:00} = 40.24\%;\ \eta_{10:00\text{-}11:00} = 43.19\%;\ \eta_{11:00\text{-}12:00} = 35.57\%;$$
$$\eta_{12:00\text{-}13:00} = 36.6\%;\ \eta_{13:00\text{-}14:00} = 39.76\%;\ \eta_{14:00\text{-}15:00} = 46.26\%;$$
$$\eta_{15:00\text{-}16:00} = 11.67\%$$

The steam has been generated for two hours from 13:30 to 15:30h. In these two hours 620ml of steam has been collected. The variation of different temperatures and solar intensity with time is shown in Fig. 7. The variation of the efficiency of collector and solar intensity with time is shown in Fig. 8.

VII. CONCLUSION

On a winter day, it is observed that steam has been generated for two hours from 13:30 to 15:30h with maximum solar intensity of 795W/m^2 and maximum ambient temperature of 19°C. In these two hours 620ml of steam has been collected. The evacuated tube solar collector attains maximum efficiency of 46.26% during 14:00 to 15:00h.

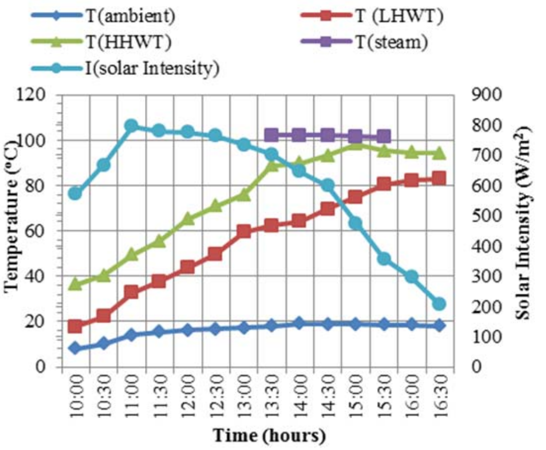

Fig. 7 Variation of temperature and solar intensity with time on 18/12/2015

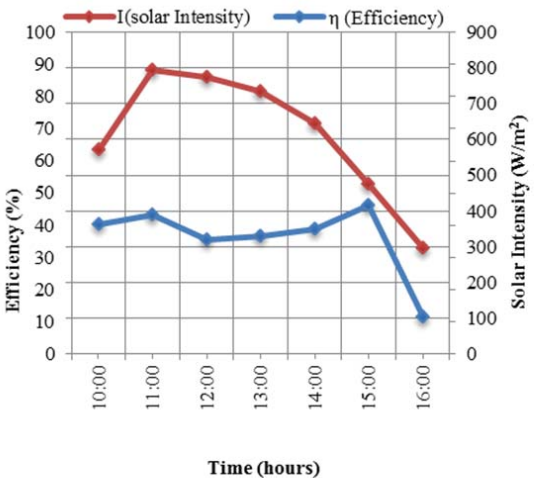

Fig. 8 Variation of efficiency of collector and solar intensity with time on 18/12/2015

Nomenclature

A	the area of evacuated tube collector	m^2
c_p	specific heat of water	kJ/kg K
c_{ps}	specific heat of steam	kJ/kg K
D_o	outer diameter of absorber tube	m
I	solar intensity	W/m^2
L_e	length of evacuated tube	m
L_v	latent heat of vaporization	kJ/kg
m_v	mass of vapour	kg
m_w	mass of water	kg
T_L	temperature at lower end of header	K
T_H	temperature at higher end of header	K
T_a	ambient temperature	K
T_s	temperature of steam	K

Greek

η	solar collector efficiency

References

[1] R Perez et al. (1995), "Calculating solar radiation received by tubular solar-energy collectors", Solar Engineering; I: 699-704.
[2] L Qin (1999), "Evaluation of evacuated tubular solar-collectors for large SDHW systems and combined space-heating systems", Proceedings of northsun99, Edmonton, Alberta, Canada.
[3] S Lart (2000), "Development of a thermal performance test for an Integrated collector-storage solar water heating system", PhD Thesis, pp 90-100, Division of mechanical engineering and energy studies, university of Wales Cardiff.
[4] L.J. Shah (2004), "Vertical evacuated tubular-collectors utilizing solar radiation from all directions", Applied Energy 78, pp 371-395.
[5] G.L. Morrison (2004), "Water-in-glass evacuated tube solar water heaters", Solar Energy 76, pp 135-140.
[6] G.L. Morrison (2005), "Measurement and simulation of flow rate in a water-in-glass evacuated tube solar water heater", Solar Energy 78, pp 257-267.
[7] Yong Kim (2007), "Thermal performance comparisons of the glass evacuated tube solar collector with shapes of absorber tube", Renewable Energy 32, pp 772-795.
[8] I. Budihardjo (2009), "Performance of Water-in-glass evacuated tube solar water heaters", Solar Energy 83, pp 49-56.
[9] Liangdong Ma (2010), "Thermal performance analysis of the glass evacuated tube solar collector with U-tube", Building and Environment 45, pp 1959-1967.
[10] Tang et al. (2011), "Comparative studies on thermal performance of water-in-glass Evacuated tube solar water heaters with different collector tilt-angles", Solar Energy 85, pp 1381–1389.
[11] Zhang et al. (2014), "Thermal performance of direct-flow coaxial evacuated-tube solar collectors with and without a heat shield", Energy Conversion and Management 84: pp 80–87.
[12] Kabeel et al. (2015), "Modified mathematical model for evaluating the performance of water-in-glass evacuated tube solar collector considering tube shading effect", Energy 89: pp 24-34.
[13] Sabiha et al. (2015), "Progress and latest developments of evacuated tube solar collectors", Renewable and Sustainable Energy Reviews 51: pp 1038–1054.