Investigations on a micro-scale solar chimney

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Abstract— Solar chimney is a promising technology to convert solar thermal energy to electricity. This system is a combination of solar air heater and a central updraft tube to generate a solar energy induced convective flow of air to drive a turbine. A micro-scale model of such a system was installed for studying its feasibility in Kerala conditions. As the mean temperature differential obtained was only about 3.3°C and the chimney height was only 3m, a low air velocity value of 1.9 m/s was observed. Even though the possibility of power production with solar chimney could be established in the study, the economic and technical feasibility of the technology was not appreciable due to the climatic and geographic conditions prevailing in Kerala.

Keywords— Solar chimney, solar updraft tower, solar air heater, solar thermal energy.

I. INTRODUCTION

Energy is considered as the key to human progress since the very dawn of civilization. There is an ever increasing demand for energy due to the increasing population and the steady improvement in living standards all over the world. Dependence on fossil fuels for energy needs has been the cause of multiple challenges in the modern era namely: depletion of fossil fuels reserves, global warming and other environmental concerns and continuing economic crisis in developing countries due to fuel price rise. Being the most abundant and well distributed form of renewable energy, solar energy constitutes a big asset for the world. Solar energy is a very large non-polluting primary source of energy, available in plenty in developing countries like India.

Out of various technologies to harvest solar thermal energy, solar chimney is a promising innovation. It is a solar thermal driven electrical power generation plant which converts the solar thermal energy into electrical power with the aid of convective heat transfer process. Solar towers had aroused the interest of many researchers around the world and as early as 1500, Leonardo Da Vinci illustrated a solar tower which he called "smoke jack" [1]. Scientists had described the conceptual possibility of using the large hyperbolic cooling towers of abandoned nuclear power plants as solar chimneys, if a transparent cover surrounding the tower base is provided to collect the solar energy along with a hot air turbine in the tower [2]. As early as 1992, an experimental solar chimney power plant was developed at Manzanares in Spain [3]. The results of the experiments conducted and the simulation could establish the feasibility of the system. There was a proposal for solar chimney power plants in Iran as the country had high direct solar radiation with large areas under desert which encouraged the project [4]. A solar chimney PV/T power plant which was a combination of solar thermal and photovoltaic technologies was developed in China [5]. New designs of solar chimneys by integrating PV are also being developed [6]. Many mathematical models have been developed to simulate the performance of solar chimney systems [7]. Investigations were also done by on the improvement of ventilation in buildings with these systems [8]. Numerical approaches to improve the design in buildings are also relevant [9]. Power production with solar chimney has also been combined with water desalination [10]. Solar chimney power plant, even though a known concept, has much relevance in renewable energy production and hence its feasibility in Kerala state of India was studied.

II. MATERIALS AND METHODS

2.1 Theoretical considerations and design procedure for solar chimney
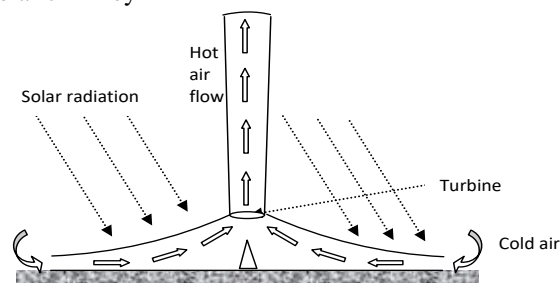

Fig.1: Concept of solar chimney

The micro scale prototype solar chimney plant consisted of a solar tower placed at the centre of a transparent canopy spread at a height above a painted black surface. The

conceptual configuration of the solar chimney is shown in Figure 1.

2.2 Design procedure for chimney:

The Mass flow rate of air was estimated considering the following basic principles:

The air entering the periphery of the collector continue to travel through the space under the canopy until it reaches the chimney. The air finally exits from the top of the chimney and the rate of mass flow is given by the following continuity equation:

$$m. = A_p U \rho_1 = A_c V \rho_2 \qquad (1)$$

Where:

m. = mass flow rate of air (kg/s)

A_p = $4LH_p$ (collector peripheral area, m^2)

L = length of the side of the collector (m)

H_p = height of the canopy at the periphery (m)

U = velocity of incoming air at collector periphery (m/s)

V = velocity of the air at chimney inlet (m/s)

ρ_1 = density of ambient air (kg/m^3)

ρ_2 = density of air at turbine temperature (kg/m^3)

A_c = cross-sectional area (πr^2) of the chimney with radius, r (m)

The pressure difference between the bottom and the top of the chimney P (Pa) is given by:

$$P = (\rho_1 - \rho_2) gH_c \qquad (2)$$

Where:

g = acceleration due to gravity (m/s^2)

H_c = height of the chimney (m)

The rising air imparts kinetic energy to a rotor placed in the chimney, causing it to rotate. The power the air turbine extracts from the rising air, P_r (W) is given by:

$$P_r = 0.5\eta_r \rho V^3 A_c \qquad (3)$$

Where:

η_r is the power coefficient of the turbine and ρ is the air density.

The pressure head due to the buoyant force can be obtained from Toriselli's equation given below:

$$V = (2gh)^{\frac{1}{2}} \qquad (4)$$

If the specific gravity of the general mass of cooler air surrounding the chimney is unity and that of hot air s_h, the net buoyant head responsible for velocity, V (m/s) is:

$$h = (1- S_h) H_c \qquad (5)$$

Where, H_c is the chimney height (m).

The value for S_h of hot air can be expressed in terms of the ratio of absolute temperatures,

$$S_h = T_c/T_h \qquad (6)$$

Where, subscripts c and h refer to the cooler and hotter air masses. Now the formula (4) becomes,

$$V = (2gH_c (1-T_c/T_h))^{\frac{1}{2}} \qquad (7)$$

The mass of gases, m flowing through any cross-section of the chimney (kg/s) is given by:

$$m = AV\rho \qquad (8)$$

$$m = \pi/4\ D^2 V\rho \qquad (9)$$

Thus, diameter of chimney D (m) is given by:

$$D = 1.128\sqrt{(mg/(V\rho g)} \qquad (10)$$

Collector dimensions:

The collector dimensions were arrived as follows:

Base length was decided to be 4m making a 4mX4m base which was painted black.

Slope of the collector roof = 30 degrees

From trigonometric ratios, the collector dimensions obtained were as below:

Slant height = (0.5) X base length/ cos 30°

= 2.165m

Altitude = (0.5) X base length X tan 30°

= `1.0819m

2.3 Test procedure

The test was performed in the prototype power plant when the solar insolation was observed to be steady and somewhat conducive to obtain reliable data. The effort was to get a condition for obtaining steady values of air velocity which gave a direct indication of the output power. Observations of air temperatures (ambient and inside the collector) and air velocities were noted from 10 am to 4 pm at hourly intervals for 5 consecutive days.

The power density, P_d (W/m^2) of the air stream was calculated using the equation,

$$P_d = 0.5\ \rho_2\ V^3 \qquad (11)$$

The air density was calculated by taking the Universal gas constant for air as 0.287 kJ/kg°K and atmospheric pressure as 101.325 kPa.

Actual power production, P_a from the micro scale unit was calculated by assuming a conversion efficiency of 0.4.

$$P_a = 0.4\ A_c\ P_d \qquad (12)$$

III.   RESULTS AND DISCUSSION

3.1 Design and fabrication of the solar chimney

Fig.2: Solar air heater

The designed and fabricated prototype solar chimney included a triangular pyramid collector along with the solar tower. The framework for collector was fabricated using MS angle iron and MS rods to get a square base. The cladding material for thermal energy trapping material was UV stabilised polyethylene sheet of 50 micron thickness. The sheet was clad on the collector framework to create a greenhouse effect for increasing the temperature inside. The collector was set at a fixed maximum height at the centre and minimum height at periphery leaving a clearance above ground level to permit the entry of outside cool air. This collector configuration was adopted to actuate the convection current which could drive the hot air upwards due to density difference. This sheet canopy supported on the framework fabricated with MS angle 32 x 32 x 3 mm size, could be placed at varying heights above the collector surface. The floor of roof terrace with a concrete surface was chosen to get a higher surface temperature than that could be produced by natural earthen ground. The collector surface was given three coatings of ordinary black paint to increase the absorptive characteristics of the surface.

The updraft tower was fabricated with a poly vinyl chloride pipe of length 3m and inside diameter 25 cm. An MS flange was used for connecting the pipe at the centre of the solar air heater (solar collector) as shown in Fig. 2. A provision for inserting an anemometer at the junction of the collector and tower was given for measuring air velocity. The design details of the solar chimney are given in Table 1.

Table 1. Design specifications of solar chimney

Size of the collector (m)	4x4
Height of chimney (m)	3
Diameter of chimney (m)	0.25
Canopy clearance at periphery (m)	0.06

3.2 Performance of the updraft tower

The experiments were conducted during the month of March at Trivandrum in Kerala state of India (8.5241°N, 76.9366°E). The temperatures Ti and To, inside and outside the collector, respectively recorded on five consecutive days at an hourly interval from 10 to 16 hours is shown in Table 2. It could be observed from Table 2 that substantial increase in air temperature could not be achieved in the morning hours. It appeared that even when there was sufficient sunshine, it took some time for the surface to get heated up and thereafter there was a steady increase in the air temperature inside the collector. The variation of mean temperature rise of air in the collector is depicted in Fig. 3. Maximum hike in temperature was

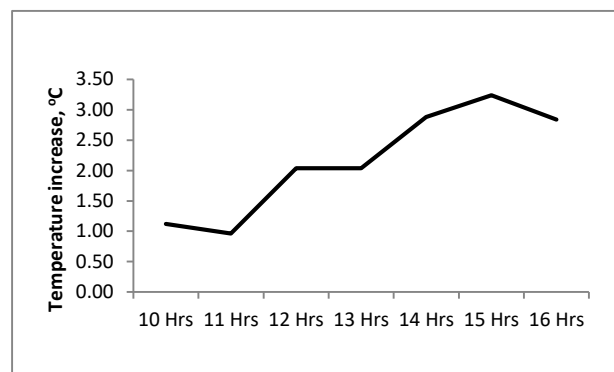observed at 3 pm and there after the temperature gradient started declining.

Fig.3: Variation of temperature gradient with time

Table 2. Temperature variation in the solar air heater

Days		Time, Hrs						
		10	11	12	13	14	15	16
Day 1	Ti	37.3	38	40	41	41.2	40.4	39
	To	36	37	36.5	38	38	37.5	36
Day 2	Ti	37	37	38.8	40	41.7	41.8	40
	To	36	37	36.5	38	38	37.5	36
Day 3	Ti	38	39	39.6	40.3	41.7	40	40.2
	To	36	38	38.3	38	39	38	38.2
Day 4	Ti	36	38.1	40.2	40	42.1	42	41
	To	37	37	38	39.3	39	40	38.4
Day 5	Ti	37.3	38	38	40.2	40.7	42.5	39.4
	To	36	36.8	37.1	38	39	37.5	36.8

The power obtainable from the air stream per unit area is a function of the cube of the air velocity and the air density. The variations of density and temperature of the air stream are illustrated in Fig.4. The upward draft of air is induced by the rise in air temperature which is responsible for the increased air velocity. Air density decreases as the air temperature increases and this is likely to have an adverse effect on the power production as the kinetic energy of the air mass is influenced by the mass of air column passing through the turbine in unit time.

Fig. 5 illustrates the power parameters of the micro-scale system. As the power in the wind is proportional to the cube of air velocity even with a slight increase in air velocity there was a significant rise in the power density of air. The effect of slight decrease in air density due to heating was not seen influencing the power density significantly. Thus it could be inferred that the air velocity varies in the solar chimney with time of the day and the power obtained was substantially high in the afternoon hours reaching maximum at about 3 pm in the climatic conditions prevalent in the test site. After that the power production seemed to decline.
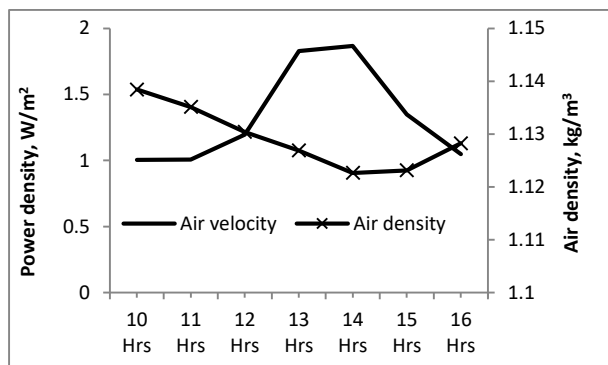
Fig.4: Variation of collector air parameters with time

The actual power produced from the micro-scale solar chimney was meager as the overall conversion efficiency was low with most plat plate collectors. In this system the solar energy was converted into thermal energy of air which was subsequently converted to kinetic energy of the air mass flowing through the chimney. The kinetic energy of the air should again be converted to mechanical energy by the turbine which in turn needs to be transformed to electrical energy. The overall efficiency of the system gets reduced due to these series of conversions. The effect of side winds may also act adversely on the air velocity inside the chimney but could not be assessed in the present study.

It can be seen from Fig.5 that the actual power produced from the micro scale model is very meager mainly due to the small height of the chimney. Chimney height is the most crucial factor in getting sufficient upward draft of air. Even though the possibility of power production by solar updraft tower could be demonstrated, the system is not expected to have substantial scope in states like Kerala where large stretches of waste lands are not available. In addition, the cloudy conditions prevalent during the monsoon season are not favourable for such a power production system. Another handicap is the lack of large stretch of waste land required for the collector. The overall inference of the study is not in favour of solar updraft towers in the state of Kerala.
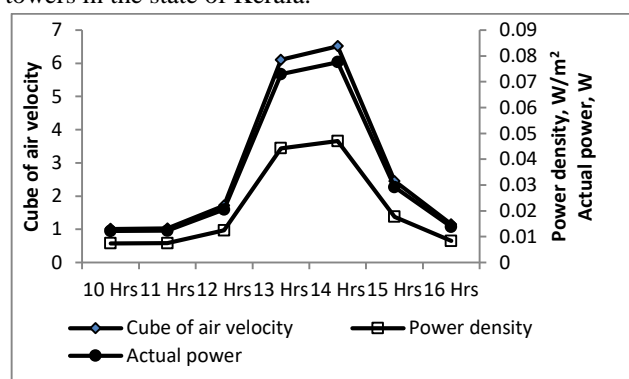

Fig.5: Variation of different parameters of power with time

IV. CONCLUSION

The following were the salient findings and conclusions of the present feasibility study on electric power production using the concept of solar chimney:

i.   The possibility of power production by solar chimney effect was demonstrated.

ii.   The relevance of the dimensions of the system on the power output could be understood. The chimney height is the most important factor affecting the air velocity which has a tremendous effect on the power output from the plant. Large collectors spanning huge areas of land are essential to produce reasonable power output.

iii. The clearance between ground and the periphery of the collector need to be optimized to reduce the adverse effect of side winds.

iv.   The ground surface (concrete roof in the present stud) acted as a storage medium storing part of heat energy from the radiations incident on the land surface during the day time. During cloudy conditions and possibly at night, this heat is released to the air in the collector which in turn can produce power, though at a reduced rate. Sensible heat storage techniques can improve the performance.

v.   Temperature differential attained during the testing period was small in the micro-scale design. A collector of more optimised design with selective coatings with high absorptivity can produce better temperature gradient.

vi.   There is not much feasibility for this technology in the state of Kerala in consideration of the climatic and geographical factors characteristic of the state.

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