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SIMILITUDE MODEL DESIGN AND PERFORMANCE EVALUATIONS OF SOLAR TOWER SYSTEM

Bashir Ahmed Danzomo[1], Sani Jibrin[2] and Mohd. Maarof B Hj Abd Moksin[3]
[1,2]College of Engineering, Science and Technology, HAFED Poly, Kazaure, Jigawa State, Nigeria
[2,3]Physics Department, Faculty of Science, University Putra Malaysia, Serdang, Selongor, Malaysia
E-Mail: sanijibringumel@yahoo.co.uk

ABSTRACT

In this study, performance evaluations of solar tower system based on the environmental conditions of Kano, Nigeria has been described by considering the simplified theories of the solar tower system and constructing a solar tower system by using the energy calculations, technical dimensions and materials for Enviromission (Australia) and Manzanares (Spain) solar tower power plants and testing the system at no-load conditions to determine the available power (power input). Result shows that, the enthalpy and entropy values increased for the solar tower system due to minimum losses from the system, which resulted to an increased energy and positive power input, $P_{input} = 7.0W$. An attempt was made to test the solar tower system "B" at load condition by selecting a dynamo of 6W electrical output, however, no result was obtained, and this was due to the higher starting torque of the dynamo.

Keywords: solar tower system, similitude, design, performance evaluations.

Nomenclature

Pi = The ideal power

$\dot{w}_b$ = Rate of work of buoyancy of the system

T_0 = Ambient air temperature, (^oC).

T_1 = Temperature of expanded air inside the collector, (^0C)

$\dot{m}_t$ = Mass flow rate of warm air inside tower (kg/s)

v_t = Average Velocity of warm air inside tower, (m/s)

c_p = Specific heat capacity of air at operating temperatures, (kJ/kgK)

g = Acceleration due to gravity = 9.81 (m/s^2)

A_t = Tower Area, (m^2)

v_{tip} = Radial speed of turbine blades (m/s)

A_c = Collector Area (m^2)

ρ_t = Density of warm air inside the tower at, (kg/m^3)

$\dot{Q}_{coll.}$ = Rate of energy loss from the collector, (J/s)

u_b = Bottom heat loss coefficient, $(W/m^{2\,0}C)$

u_f = Front (roof) heat loss coefficient, $(W/m^{2\,0}C)$

$u_{coll.}$ = Collector heat loss coefficient, $(W/m^{2\,0}C)$

h = Specific enthalpy, kJ/kg

INTRODUCTION

The Solar Tower System is a type of renewable energy power system in which air is heated in a circular greenhouse like structure (solar collector) and the resulting convection causes the air to rise (due to buoyancy) and escape through a central tube (the tower). The moving air drives turbine which produce electricity by a generator. The system is mainly a set of three components as shown in Figure-1, (Joy, 2007):

- Circular Collector of diameter D_{coll} supported above the absorber and covered by a transparent glazing (The green house),
- A tall air drafting tower in the center of the solar collector with internal diameter D_t, and height H_t,
- Air Turbine, around the bottom of the tower system.

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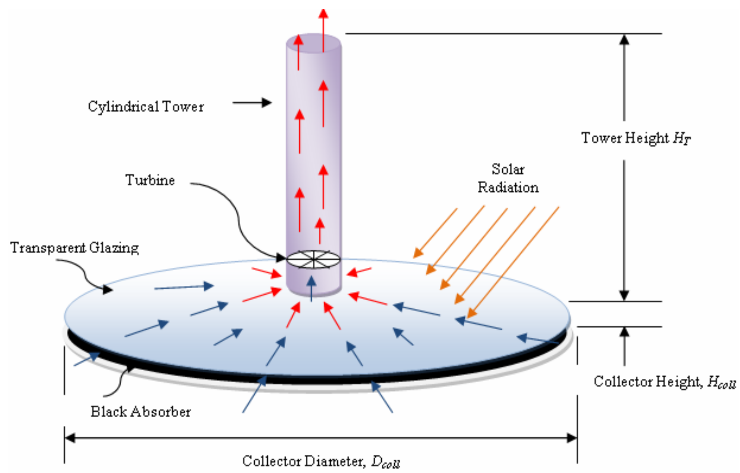

Figure-1. The solar tower system.

As shown in Figure-1 above, air is heated by solar radiation under a circular transparent roof (glazing) open at the periphery (which serve as the air inlet). When this air becomes hot, it expands, and become less dense. As hot air is lighter than cold air, the air rises up the tower due to buoyancy force. Suction from the tower continuously draws in more hot air from the collector, and cold air (ambient air) comes in from the collector roof periphery. The energy, which is the buoyancy work contained in the updraft of the air is converted into mechanical energy by the rotation of the turbine (set at the base of the tower), and to electrical energy by a generator, (Duffie and Beckman, 1991).

Historical Backgrounds

In 1903, Spanish colonel Isidoro Cabanyas first proposed a solar chimney in the magazine "La energia electrica", (http://en.wikipedia.org/wiki/solar_updraft_tower, 2006). One of the earliest descriptions of a solar chimney power station was written in 1931 by a German author, Hanns Gunth (http://en.wikipedia.org/wiki/solar_updraft_tower, 2006). Shlaigh (1995) built a working model of a solar chimney power plant in Manzanares (Spain). This power plant operated successfully for approximately 8-years and the maximum power output was about 50kW. Gannon and Backstrom, (2003) presents a thermodynamic cycle analysis of the solar chimney and also an analysis of turbine characteristics.

Schlaich, (2007) proposed initial physics to explain the solar chimney technology operation with tall chimneys up to 1000m, (Ruprecht *et al*., 2003). Schlaich and Bergermann, (2007) gave results from fluid dynamic calculations and turbine design for a 200MW solar chimney. A thermal and technical analysis targeting computer aided calculations was described by Bernades and Dos-Santos, (2003). The "Enviromission" Ltd of Australia (Schlaich and Bergermann, 2007) and "Solarmission" technology of U.S.A intended to begin construction in early 2007 of the first full size solar chimney power plant of 200MW output in Australia. The power plant will have a chimney of 1000m with internal diameter of 130m and a circular solar collector of diameter 7000m. This power plant has the brand name "*Solar Tower*". Main dimensions and technical data of the Manzanares and Enviromission solar tower plants are shown in Table-1.

Table-1. Technical data of Manzanares and enviromission solar tower power plants.

Properties	Manzanares	Enviromission
Collector diameter (D_{coll}) m	224	7000
Tower height (H_{tower}) m	195	1000
Collector height (Z) m	1.85	20
Collector area (m^2)	39408	38.5 x 10^6
Tower diameter (m)	10	130
Tower area (m^2)	78.5	13273
Mass flow rate (m) kg/s	860	282000
Electrical power output (kW)	50	200,000

Source: Schlaich and Berger Mann, (2007)

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Problems Statement

At present, the fossil fuels (Coal, Petroleum and Natural gas) together with nuclear fission and hydroelectric power represent the only well-developed means of generating large quantities of electric power (Papa Georgiou, 2005). The global warming effect due to fossil fuel is a real threat, following the current trend, CO_2 emission will be doubled in next 30-40 years, (Papa Georgiou, 2005). Disposal of radioactive wastes presents a serious problem; some of the waste products are radioactive and will remain so for 100 years or more. It is assumed that by the years 2050, sites for large scale hydro projects may become difficult to find as global water level may decline because of global warming due to continuous emissions of carbon dioxide greenhouse gases, (Sabo, 2006).

The Intergovernmental Panel on Climate Change (IPCC) indicated that: "Linear regression of 1901-1990 rainfall data from 24 stations in the west African Sahel yields a negative slope amounting to a decline of 1.9 standard deviation which showed a persistent downward trend" (IPCC, 1997). The solar tower technology can cover the world's energy demand (in electricity and any future transportation fuels based on Hydrogen), it operates naturally and it's reliable and pollution free. Consequently in desert areas with inexhaustible sand and stone, solar tower can reproduce itself, (Duffie and Beckman, 1991). However, conditions in Nigeria are very favorable for Solar Tower System, insolation levels are high, there are large abundant areas of flat land and the demand for electricity increases, (NJSE, 1989).

Objective of the study

The objective of this study is to develop a model solar tower system from the energy calculations and technical data of Manzanares solar power plants based on hydraulic similitude design methodology and perform experimentation on the system using the environmental conditions of Kano, Nigeria.

The fundamental equations

The fundamental equation for the operation of the solar tower system, i.e., the electrical power output, P_E of the system is given by the relation,

$$P_E = P_{input} \times \eta_T \quad (1)$$

The optimum performance of the air turbine as a function of flow air velocity entering the turbine v_t has been described by Papa Georgiou, (2005):

$$\eta_T = \frac{v_t}{v_{tip}} \quad (2)$$

Power input to the turbine, P_{input} is determined from the relation,

$$P_{input} = Pi - \dot{Q}_{coll.} \quad (3)$$

But,

$$Pi = \dot{m}_t \times w_b \quad (4)$$

And also,

$$\dot{Q}_{coll} = u_{coll} \times A_{coll} \times (T_1 - T_0) \quad (5)$$

However, the updraft of air flow rate inside the tower $\dot{m}_t$, rate of work of buoyancy of the system, $\dot{w}_b$ and the collector heat loss coefficient, $u_{coll.}$ is given by the equations:

$$\dot{m}_t = \rho_t \times A_t \times v_t \quad (6)$$

$$w_b = -\left[(\Delta h) + g(\Delta H_t) + \tfrac{1}{2}(\Delta v_t^2\right] \quad (7)$$

Similitude Model Design and Scaling

To achieve similarity between the proposed model solar tower system and the Environmission power plant which also act as a prototype solar tower system, all the corresponding pi-terms must be equated between the model and the prototype. However, a model is said to have similitude with the real application if it share geometric, kinematic and dynamic similarities between model and prototype.

The basic and the most obvious requirement of similitude is that the model be exact geometric replica of the prototype. In this form, the model is a geometrical reduction of the prototype and is accomplished by maintaining a fixed ratio for all homologous geometric dimensions between the model and the prototype by applying the homologous subscript values, *r* for the scaled ratio, *p* for the prototype and *m* for the model.

The pi-terms involved in the geometric similitude includes ratios of the important lengths, L, or height, H, thickness, t, diameter, d, area, A and volume, *V* of the model scrubber system.

$$\Pi_{1m} = \phi\,(l_„\ h,\ t,\ d,\ A,\ V) \quad (8)$$

Therefore, the scaled geometric dimension of the model solar tower can be determined by:

$$\frac{L_p}{L_m} = \frac{d_p}{d_m} = \frac{H_p}{H_m} = \frac{t_p}{t_m} = L_r = d_r = H_r = t_r \quad (9)$$

An area, *A* is a product of two homologous lengths; hence, the ratio of the homologous area is also a constant and can be expressed as:

$$\frac{A_p}{A_m} = \frac{L^2{}_p}{L^2{}_m} = L^2{}_r = A_r \quad (10)$$

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From Table-2 above, the prototype (Manzanares solar tower plant) is having a collector and tower diameters of 224m and 10m and collector and tower heights of 1.85m and 195m, respectively. Considering a ratio of 100 and equation (1), the geometrical dimensions of the model solar tower system is determined below.

$$\frac{d_{pC}}{d_{mC}} = L_r = 3000 \Rightarrow d_{mC} = \frac{224}{100} = 2.24m \therefore the\ collector\ diameter,\ d_{mC} \approx 2.20m$$

$$\frac{d_{pT}}{d_{mT}} = L_r = 100 \Rightarrow d_{mT} = \frac{10}{100} = 0.1m \therefore the\ tower\ diameter,\ d_{mT} = 0.1m$$

$$\frac{H_{pT}}{H_{mT}} = L_r = 100 \Rightarrow H_{mT} = \frac{195}{100} = 1.95m \therefore the\ tower\ height,\ H_{mT} = 1.95m$$

$$\frac{H_{pC}}{H_{mC}} = L_r = 100 \Rightarrow H_{mC} = \frac{1.85}{100} = 0.0185m \therefore the\ collector\ height,\ H_{mC} \approx 0.019m$$

The geometry of the model solar tower system is tabulated below:

Table-2. Solar tower system geometry.

Property	Model solar tower system
Collector diameter, (m)	2.200
Collector height, (m)	0.019
Tower height, (m)	1.950
Tower diameter, (m)	0.100

MATERIALS AND METHODS

Selection of materials for the model solar tower system was made by considering the materials for 224m Manzanares solar tower power plant, strength, availability, affordability and ease of fabrications. An electric arc welding was selected for the fabrications of the collector frames, (this was due to the availability of the equipment and the economics of the process, George, 1991). While bolts and nuts were used to assemble the removable parts. Mild steel bar and rods was selected for the construction of frames for the circular collector, this was to provide shape and good flow characteristics of the hot air from the collector to the cylindrical tower. The selection of soil as absorber surface was made due to the higher roughness factor of the soil which facilitates the heating of the air as well as its natural heat storage property. The developed model is shown in Figure-2.

Figure-2. The model solar tower system.

EXPERIMENTATIONS

Six months test were conducted on the model solar tower system from November, 2007 through January, February, March and April, 2008, respectively. An average data for the six months is presented in this study. The experimentation instruments comprised of a hot-wire anemometer, solarimeter and mercury in glass thermometers as shown in Figure-3. The Hot-wire anemometer were used to take both the readings of temperatures and wind velocities at four tower stages (4 holes drilled on the tower for taking readings), inside the collector, and at the tower exit. The ambient and wind velocities of the test area were taken at the same time (using the hot-wire anemometer) while readings for the solar radiations were taken using the Solarimeter. However, the glazing and soil temperatures were taken using mercury in glass thermometers.

Figure-3. Instruments for the experimentation.

RESULTS

An average reading for the six months were tabulated, as shown in Table-3, their average values were further interpolated at operating temperatures using Table of thermodynamic transport properties of fluids and considered to be used in the performance analysis.

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Table 3. Average (6 Months) test data for solar tower system.

Date	T_o (°C)	T_1 (°C)	T_2 (°C)	T_3 (°C)	V_t (m/s)	T_{gla} (°C)	T_{soil} (oC)	V (m/s)	G_T (w/m)
Nov	36.0	41.2	42.5	34.1	0.8	38.0	42.2	1.8	601
Dec	36.5	42.9	42.7	36.7	0.6	38.7	42.8	0.2	735
Jan	37.0	44.5	45.2	42.2	0.9	39.9	46.7	2.8	854
Feb	36.5	44.1	43.0	40.2	1.0	38.9	45.8	1.5	800
Mar	43.0	42.4	43.8	37.0	0.8	37.7	44.4	0.7	876
Apr	45.0	44.6	43.7	41.1	0.8	41.0	47.4	0.9	912
Average	39.00	43.28	43.48	388.55	0.82	39.00	44.90	1.32	796.33

The average were further interpolated and applied in the performance analysis of the model system using the relevant fundamental equations. The analyzed result is shown in Table-4.

Table-4. Result of the performance analysis.

Property	**Model system**
Collector area, A_{coll} (m^2)	3.142
Tower area, A_t (m$^{2)}$	0.00567
Mass flow rate, m_t (kg/s)	0.005199
Collector heat loss, $Q_{coll.}$ (J/s)	17.5
Work of buoyancy, W_b (J/kg0	4720.97
Ideal power, P_i (W)	24.54
Power input to turbine, P_{input}, (W)	7.04

Considering the performance analysis, it has been observed that, increasing the size of the solar tower system increased its efficiency and output. Also, due to the higher roughness factor and storage property of soil (used as absorber surface), the heating value of the air inside the collector was facilitated and the transition between the collector and tower base was obtained and this provided free flow of air at minimum friction loss. Due to this, the enthalpy of the hot air inside the collector increased to a value of 4737 J/kg as such, the thermodynamic work was done by the system and positive power to the turbine was obtained to be P_{input} = 7.0W.

CONCLUSIONS

This work described the development of a similitude model solar tower system using the energy calculations and technical data of Manzanares (Spain) solar tower power plant based on the environmental conditions of Kano, Nigeria. An experimental test was conducted at no-load condition to analyses the system performance on hourly basis for a period of six months from which average data of the months were analyzed and interpolated with detailed calculations performed. Due to minimum losses from the system, higher enthalpy and entropy were obtained which resulted to an increased energy and positive power input, $P_{input} = 7.0W$. An attempt was made to test the system at load condition by selecting a dynamo of 6W electrical output, but, no result was obtained, and this was due to the higher starting torque of the dynamo.

Finally, solar tower system can be constructed from cheap and available materials, there is no ecological harm no consumption of resources, even in desert areas with exhaustible sand and stone, solar towers can reproduce themselves, a truly sustainable source of energy. It is concluded that the new technology of the system can be utilized by considering the recommendations presented in this work, at least the system has performed half way by considering the no-load tests conducted and is quite applicable in Kano environmental conditions.

RECOMMENDATIONS

It is recommended that further researches should be conducted on the new technology of solar tower system; the system should be designed (with the appropriate turbine) using computer simulations by considering the following:

- Energy calculations of Manzanares and Enviromission solar tower power plants,
- Technical data and materials of the Manzanares solar tower power plant.

Considering the fact that the thermodynamic efficiency of the system increases with tower height and collector diameter, such system should be constructed in large scale and tested in an area of flat land (with no terrain for the blockage of the available wind and solar radiations).

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