Design of a Solar Updraft Tower Power Plant for Pakistan and its Simulation in TRNSYS

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Abstract-Solar updraft tower is a distinct and novel combination of three old concepts that are green house effect, chimney effect and wind turbine. It can be employed, with almost negligible maintenance cost, in electricity generation. Given the different climatic and economical conditions for different places, every region demands a specific design. As solar chimney power plant is a relatively new technology, much effort has not been done in evaluating the performances of the various plants. In this context, a solar updraft tower has been designed for the conditions of Pakistan (Lahore) and is simulated in TRNSYS to analyze the plant performance through different seasons and time of the year. The study reveals important results about the factors involved in determining the final output power produced. It is observed that the solar irradiance plays a more significant role in power generation than ambient temperature. The more the capacity of a plant to produce power, the more economical it would be. TRNSYS based program is presumed to be a handy mode of examining solar chimney power plants.

Keywords-Solar Updraft Tower Power Plant, Solar Tower, Simulation, TRNSYS, Power Generation.

I. Introduction

The scarcity of conventional energy resources and the incessant demand of energy have raised the energy cost to higher levels. In view of these circumstances, research for new and reliable energy resources got stimulated. Solar updraft tower technology is a new concept of harnessing solar energy at large scale. It uses three age old concepts of greenhouse effect, chimney effect and wind energy in its three major components i.e. collector, chimney and wind turbine respectively.

Collector is a simple glass cover surface, placed at some height from the ground, embracing a large area. At the centre of collector a very long tower is erected and at the base of this elongated tower a wind turbine is installed with generator. Solar irradiance, both direct and diffuse, heats the air present underneath the collector cover (greenhouse effect). As the temperature of the air rises, its density decreases and it starts moving upward and towards the centre of the collector. Due to the pressure difference of air inside the collector and the ambient, this heated air rises upward in the chimney (chimney/stack effect). The wind turbine, positioned at the base, uses the kinetic energy of this flowing air and converts it into rotational energy (wind turbine principle). This rotational mechanical energy is further utilized in producing electricity via generator. Subsequently, solar collector is the basic heat source, the tower is the heat engine, and the wind turbine along with the electricity generator is power unit.

II. Literature Review

The credit of solar updraft tower technology is attributed to Isidero Cabanyes, who proposed it in 1903. It was later presented by Gunther in 1931. More recent work in this field has been done by J. Schlaich who introduced basic equations to find the power output [i]. Most researchers focused in validating the concept, the power production appraisal and the economical evaluation of the system. Most proven example of the validation of this principle is the prototype pilot plant that operated during the 1980's. Though it stopped working after seven years yet it proved to be the best practical instance of the concept [ii-iii].

Further small scale projects were also developed to evaluate the performance [iv-vii]. Mathematical models were also presented by different researchers to estimate the productivity of plants [vii-xi]. Determination of different heat transfer coefficients was done [xii]. Environmental impacts and atmospheric effects have also been discussed [xiii-xiv]. Turbine performance characteristics were calculated by numerical analysis and simulation [xv]. Economic feasibility has been derived by considering initial investment [xvi]. Also some novel concepts were brought to light by researchers lately such as sloped collector, solar 'mountain-hole' power plant, inflatable chimney etc [xvii-xviii]. The rapid development of this technology along with these fresh concepts presents a picture of sustainable future.

To determine the power output of plant, ratio of pressure drop across the turbine to the total available pressure is very important. Different researchers have taken different values of this ratio. The optimum ratio is taken as 2/3. According to our assumptions this is valid until the air temperature increase is constant.

III. SYSTEM MODEL

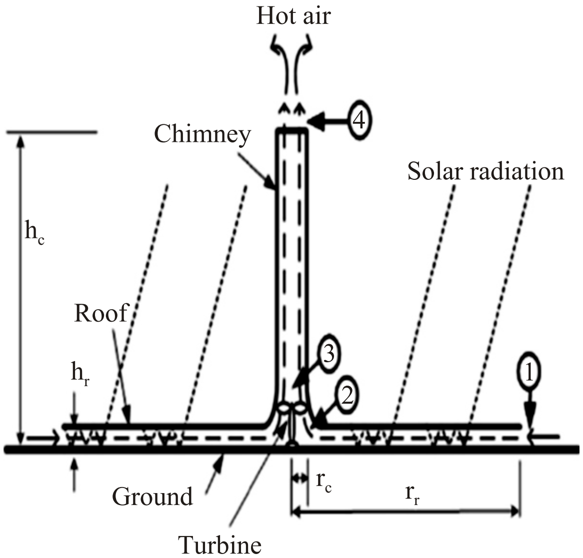


Fig. 1.

A. Nomenclature

A_{coll}: Collector Area, m^2
A_{Chim}: Chimney Area, m^2
cp: specific heat capacity at constant pressure,J/(kgK)
g: gravitational acceleration, m/s^2
G; Solar irradiation
H_c: chimney height, m
h_r: roof height above the ground, m
□: mass flow rate, kg/s
P: pressure, Pa
Q_{useful}: insolation, W/m^2
R: ideal gas constant, J/kg K
r_c: chimney radius, m
r_r: roof radius, m
T: absolute temperature, K
V: flow velocity, m/s

B. Greek Symbols

ΔT: temperature rise between ambient and collector outlet, K
g: specific heat ratio
□; Efficiency

C. Subscripts

1, 2, 3, 4: position along chimney (as in Fig. 1)
chim: chimney
Coll:collector

IV. DESIGN METHODOLOGY

The design methodology followed in this paper is adopted by Atit and chitsomboon in [xix]. Initially mass flow rate is assumed according to the requirement. After that with the help of different equations T_2, P_2, ρ_2, P_4, and Q_{useful} is obtained. Then the value of P_3 is guessed. Further T_3,T_4,ρ_3,ρ_4 are calculated. Now the value of P_3 is calculated. If the difference between the guessed value and calculated value is beyond the acceptable range then another set of calculations (iteration) is done for T_3,T_4,ρ_3,ρ_4. It is repeated until we get the desired value. After that we move to find the total pressure available to drive the turbine and the power output.

The equations involved in finding the above mentioned values are detailed below [xix];
Useful energy gain can be estimated by:

$$Q_{useful} = \eta_{coll} G A_{coll} \tag{1}$$

It is then used to determine Temperature of airflow present inside the collector.

$$T_2 = T_1 + Q_{useful} / \dot{m} C_p \tag{2}$$

Pressure at turbine inlet:

$$P_2 = P_1 + (\dot{m} Q_u / 2\pi h_r^2 \rho_1 C_p T_1 A_{coll}) \ln(r_r/r_c) - \dot{m}^2/2\rho_1 (1/A_{chim}^2 - 1/A_{coll}^2) \tag{3}$$

Density at turbine inlet:

$$\rho_2 = P_2 / RT_2 \tag{4}$$

Pressure at chimney outlet:

$$P_4 = P_1 (1 - gH_{chi} / C_p T_1)^{Cp/R} \tag{5}$$

Temperature at turbine outlet:

$$T_3 = T_2 (P_3 / P_2)^{\gamma - 1/\gamma} \tag{6}$$

Density at turbine outlet:

$$\rho_3 = P_3 / RT_3 \tag{7}$$

Temperature at chimney outlet:

$$T_4 = T_3 - gH_{chi} / C_p \tag{8}$$

Density at chimney outlet:

$$\rho_4 = P_4 RT_4 \tag{9}$$

Pressure at turbine outlet:

$$P_3 = P_4 + (\rho_3 + \rho_4) gH_{chi} / 2 + (\dot{m} / A_{coll})^2 (1/\rho_4 - 1/\rho_3) \tag{10}$$

Finally the output power:

$$Power_{output} = 2m^{\cdot}(\rho_2 + \rho_3)(P_2 - P_3) \quad (11)$$

TABLE I
TECHNICAL DETAILS

Tower Height	H_{chi}	300m
Tower Radius	r_c	5.08m
Collector Radius	r_r	128m
Collector Roof Height	h_r	2.1m
Collector Efficiency	$\square_{coll}$	25%
Collector Material		Glass
Collector Material Thickness		0.04m
Turbine Efficiency	$\square_t$	75%
Tower Material		Concrete

TABLE II
AMBIENT CONDITION

Power Output (Designed)	70 kW
Global Solar Radiation (Avg.)	600W/m2
Ambient Temperature (Avg.)	300 K
Ambient Pressure (Avg.)	98000Pa
Updraft Wind Speed	18 m/s

V. TRNSYS; TRANSIENT SYSTEM SIMULATION

TRNSYS program is software that simulates the behavior of transient systems (those systems whose output change with time). It understands a system described language in which the user specifies the components that comprise the system and the way in which they are linked. TRNSYS is appropriate for in depth analyses of any system whose performance is dependent on the passage of time. Main applications include: solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, fuel cells [xx,xxi]. TRNSYS works on the black box model where the user only needs to give inputs and static parameters to get outputs through the TRNSYS program. The outputs are solved in the user defined code which can be developed, using C, C++, FORTRAN, EES, Excel, and incorporated in the TRNSYS program.

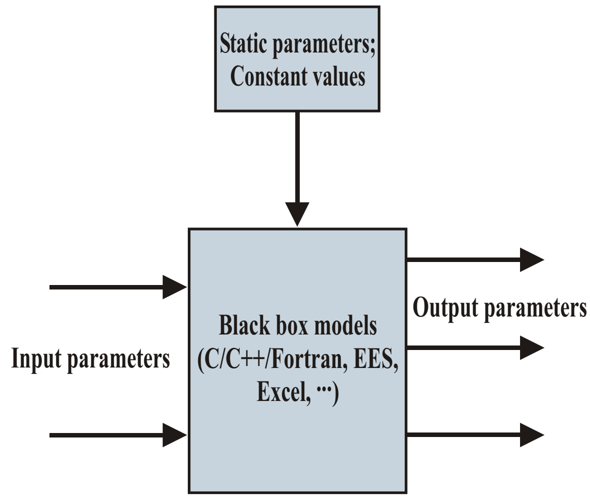


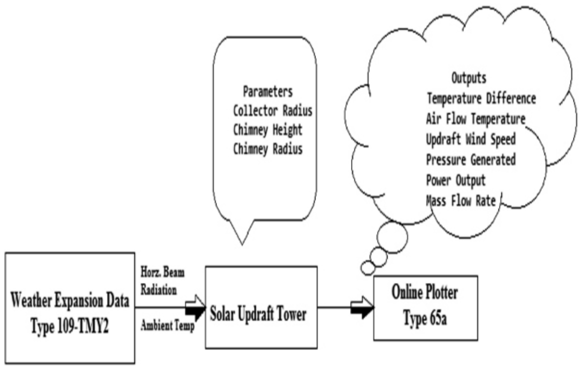
Fig. 2. Black box Model

Using TRNSYS for solar updraft tower technology has its added advantages. It provides a comprehensive weather data for a large number of regions around the globe with the necessary required details. Systems can be simulated for a day or for a year, as per requirement. The modular structure of TRNSYS gives a clear program.

VI. SIMULATION ON TRNSYS

After defining the mathematical model and equations for the system, certain constant parameters were set for our design. These constant inputs are collector radius, collector roof height, chimney radius, chimney height etc. The variable inputs include the solar irradiation and the ambient temperature. These variable inputs are provided by weather expansion data available in TRNSYS.

The first step is the creation of component. The model/equations were converted into C++ code. This was then transformed into the TRNSYS component and added to the TRNSYS library. Now the component was available to have simulation in the TRNSYS. To get simulation for a system, it is needed to give some input and have the output in desirable form. To achieve this, three components were linked together in the TRNSYS studio.



The built Trnsys program and the transferred data between TYPES

Fig. 3.

1. Weather Expansion Data
2. System component
3. Online Plotter

Weather Expansion Data provides the variable inputs, and the online plotter displays the output results in the graphical form. The links among the components can be seen in Fig. 3.

VII. RESULTS AND DISCUSSIONS

A. Simulated Outputs for a Whole Year

The graphs for different entities provide an easy key to see the results for the system for any stipulated period of time. We can plot them for a day or for a year. These graphs display the results for 8760 hours/365 days/1 year. With the help of these graphs, the system performance can be analyzed for a year. Different trends can be observed for different seasons i.e. for summer and winter (See Fig. 4-9).

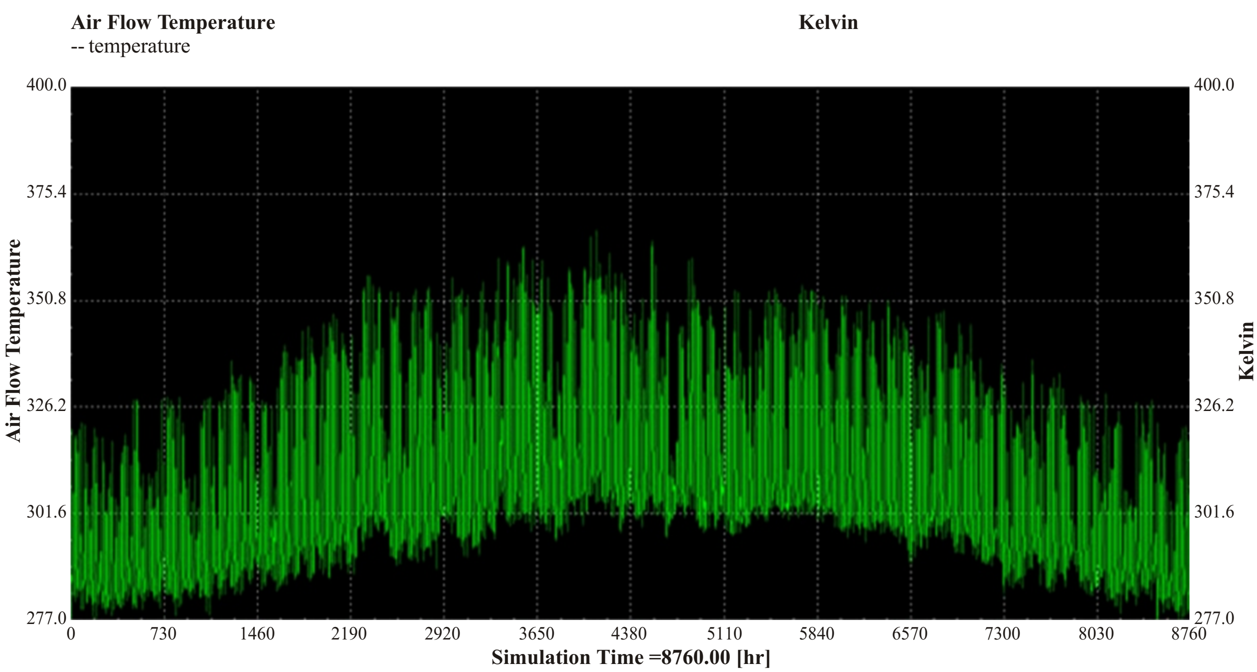


Fig. 4. Air Flow Temperature

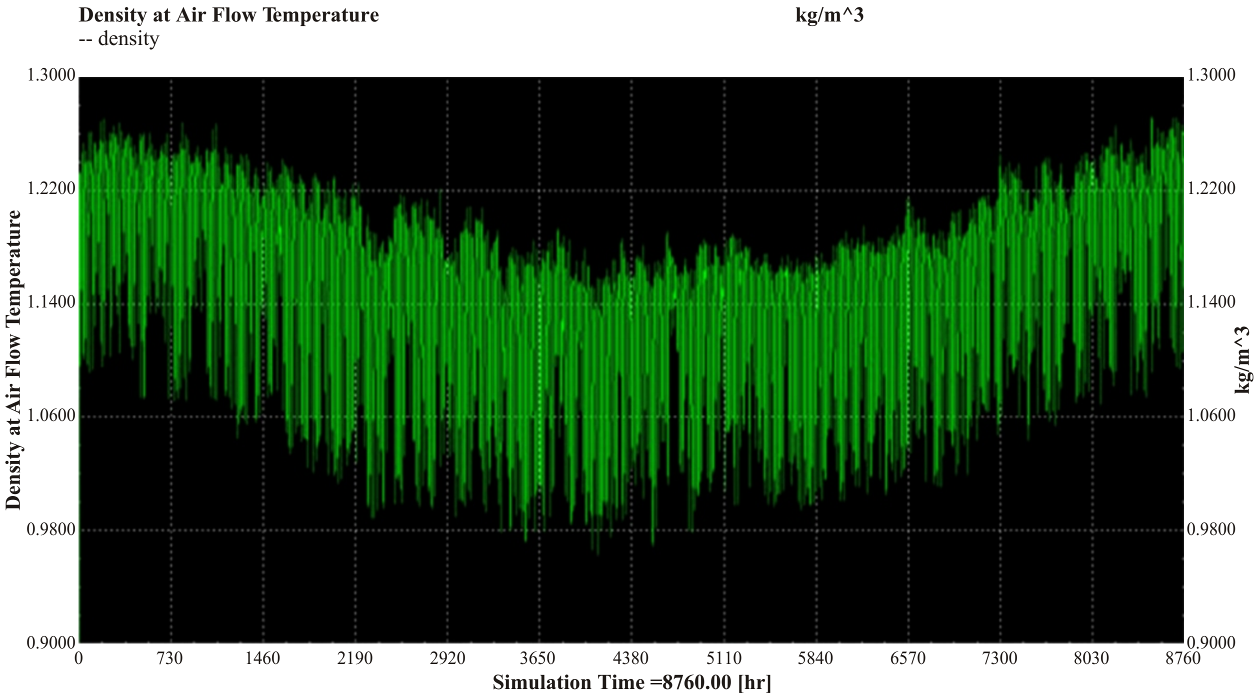


Fig. 5. Density at Air Flow Temperature (kg/m^3)

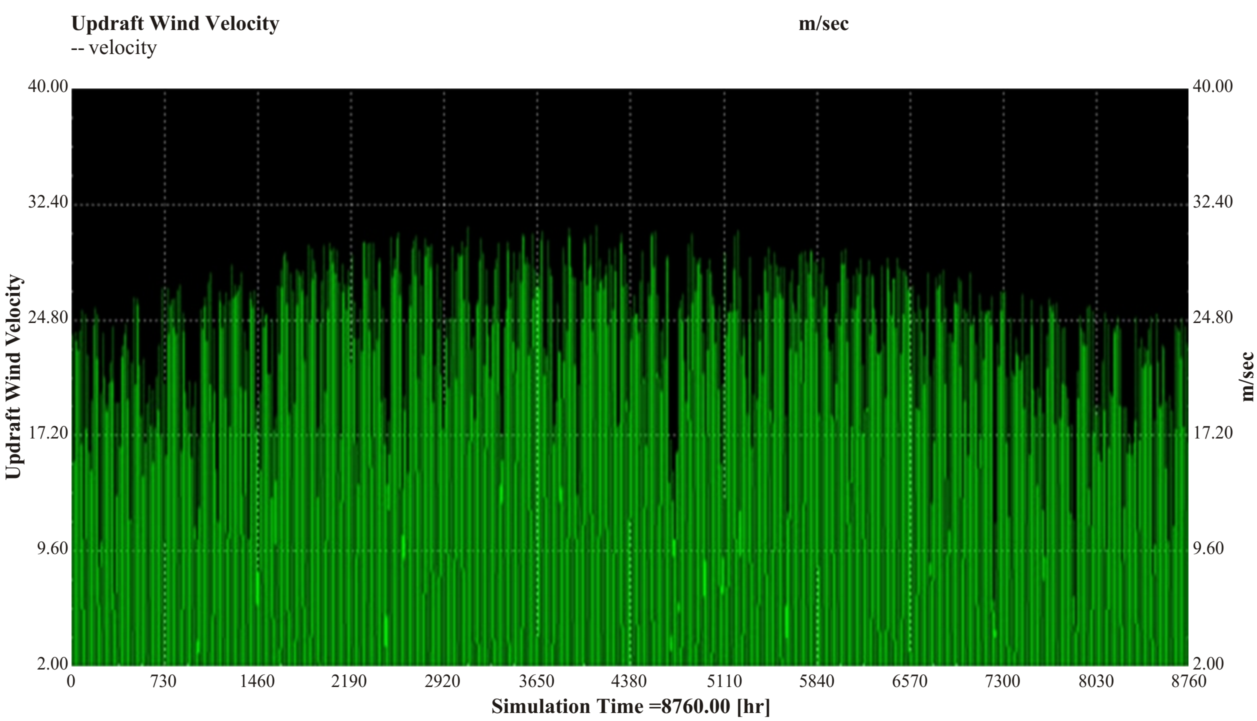


Fig. 6. Updraft Wind Velocity (m/sec)

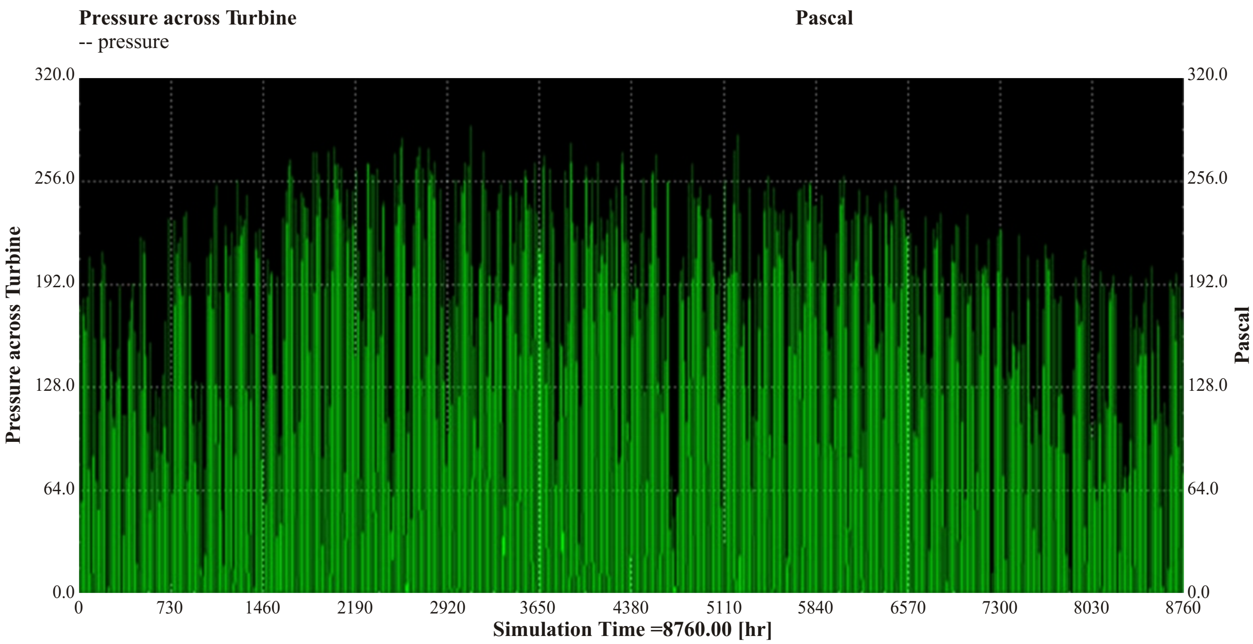


Fig. 7. Pressure across Turbine (Pa)

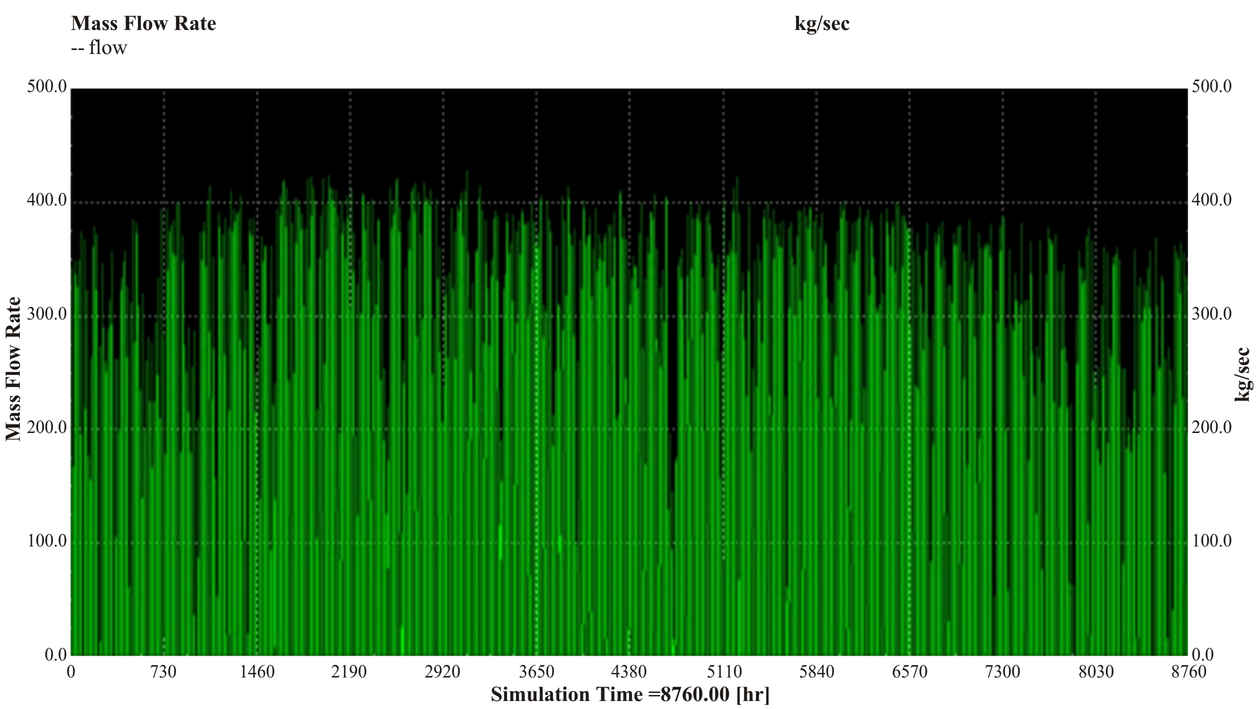


Fig. 8. Mass Flow Rate (kg/sec)

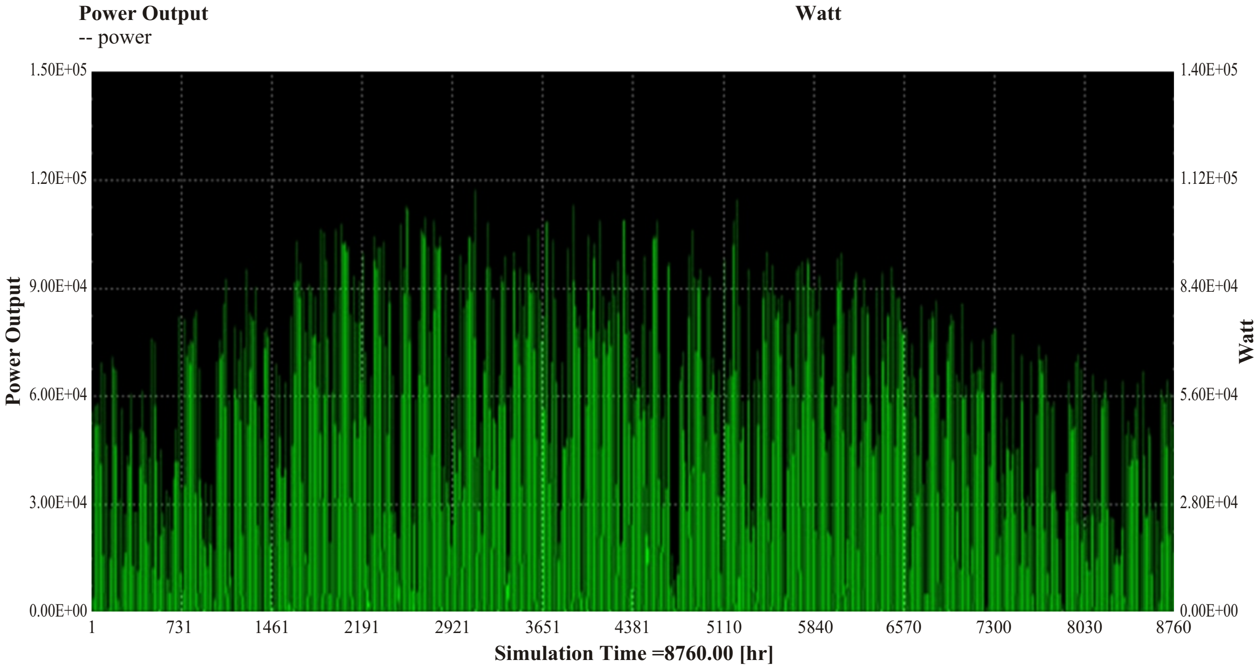


Fig. 9. Power Output (W)

B. Comparison between the Theoretical and Simulated Results

The results of theoretical calculation and simulated values are in complete conformity. The model is tested against the practical data from Manzaneres Spain prototype, and it was in complete accord.

TABLE III
THEORETICAL RESULTS

Air Flow Temperature (K)	334.5
Density at Air Flow Temperature (kg/m^3)	1.038
Updraft Wind Speed (m/sec)	20.1
Pressure Generated (Pa)	205
Mass Flow Rate (kg/sec)	350
Power Output (kW)	70

TABLE IV
SIMULATION RESULTS (PEAK VALUES)

Air Flow Temperature (K)	367
Density at Air Flow Temperature (kg/m^3)	1.27
Updraft Wind Speed (m/sec)	31
Pressure Generated (Pa)	291
Mass Flow Rate (kg/sec)	429
Power Output (kW)	117

VIII. CONCLUSION

In this study a solar updraft tower has been designed for the conditions of Pakistan (Lahore). Simulation of the designed outputs has been done in TRNSYS program. The graphs show the outputs for a period of one year. It has been observed that the solar irradiation is the most important factor in determining the power output of the system. It is deemed that TRNSYS software can be a handful tool in analyzing the performance of solar updraft power plants. The designed system can be made further improved by taking night power production into account.

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