Design and Fabrication of Solar Updraft Tower and Estimation of Power Generation; Initially Focused on Bangladesh

F Ayub¹, S Akhand¹, A S Khan¹ and G Saklayen¹

1 Faculty of Mechanical Engineering, Military Institute of Science & Technology, Bangladesh
E-mail: fayrouz.ayub@gmail.com, akhand.saarah@gmail.com

Abstract. In our studies we focused on area of sourcing, converting and delivering sustainable energy, concentrating at the potential role of solar power. Power generation through a solar updraft tower (SUT) has been a promising approach for sustainable generation of renewable energy. Developing nations are faced with many challenges. Conventional sources are insufficient to meet the increasing demand of a developing, industrious nation (e.g. Bangladesh). Our project aims in reducing electricity crisis and forming a solution for our country, Bangladesh. The electricity generated can be supplied to the national grid. This will mean reduced cost for the government in the long run and also allow the government to reduce its dependency on costly and unsustainable fossil fuel. This cost reduction benefit can be passed on to the public as reduced energy cost or preferably through nationwide energy infrastructure development. This technology will not only help with the energy concern of Bangladesh but also will help to improve the situations of other developing countries alike Bangladesh. All in all implementing this technology will pave the way towards a better world and form a part of an integrated ecosystem of sustainable energy technology.

1. Introduction
Bangladesh along with other developing nations is facing the challenge of industrialization, population increase and urbanization and is also suffering the dire consequences of these factors. These changes are causing significant amount of energy consumption which also places a great pressure on government due to scarcity of resources of conventional fossil-fuel. Alternative solutions to these problems are to depend on renewable energy resources. Solar energy is one of the renewable energy sources that represents totally non-polluting, inexhaustible, abundant energy resource and can be utilized to supply world’s needs [1]. Among many solar energy technologies the solar updraft power plant is a noble promising technology which can be used to supply power to countries with large wastelands or unused desert lands [2].

A traditional solar updraft power plant system consists of a tower, collector and a turbine or several pressure based turbines [3]. During daytime, solar radiation passes through the transparent collector roof and heats the air inside the whole collector area. Heated air induces buoyancy effect and results in large pressure drop under the center of collector which causes a strong airflow through the tower, and is used to drive turbine within solar tower to generate electricity. The concept of SUTPP (solar updraft tower power plant) was first developed by Schlaich, and a prototype was put in operation during 1980s[4], [5]. Cheap building materials, negligible hazardous waste generation, low operating costs these advantages made this renewable energy technology attractive to countries with vast unused deserts and wastelands[6]. Solar energy is a great source of renewable energy in Bangladesh due to its
geographical and climatic conditions. So, we tried to focus on how to utilize solar energy by modeling and fabricating a SUT prototype. Our data clearly showed that SUTPP even in a smaller size can be very effective to undermine the energy problem in rural areas of Bangladesh. It can further be useful for building up a larger SUTPP as we measured our data on various times around the year. In this paper, experimental setup and working procedure along with necessary data and calculations has been presented. The limitations that we had during this working experience and ways to overcome those limitations has also been discussed.

2. Construction and design parameter

2.1. Model-1
Before proceeding to main model of SUT(solar updraft tower), construction and simulation(Appendix-1) of a theoretical ratio base model was done, which was different from main prototype in both material and design. The tower of this model was of long hard paper roll, which was colored black externally, to absorb maximum amount of heat. It was effective in a way that it had a thermal conductivity of 0.05 W/(m K). The Collector material used in model was made of talc paper. The propeller was made of normal paper as the initial torque needed was low. There was no electrical connection in this model-1. So after the successful rotation of the propeller located inside the tower we decided to make our prototype.

2.2. Prototype
Modification of collector material was compulsory after observing model-1 collector efficiency (Appendix-2). PVC sheets of 0.9mm thickness was used for the prototype collector (Appendix-3). The tower was of PVC also and was about 1.7m in height. The pipe was black colored both internally and externally. The tower was supported by steel round frame. The whole structural layout was designed in such a way that it was strictly stable with steel as its core material. The frame was supporting the whole experimental setup. The turbine was made of polyethylene terephthalate (PET). The collector diameter De was selected as 1.8283m (6 ft) considering availability of space on the selected place. The ratio of collector diameter to the tower diameter is called the diameter ratio (DR) [7], [8]. The 50 kW plant in Manzanares has DR= 20 [9]. For our plant DR=12(approximately) was selected considering availability of tower material in the local market. Thus the tower diameter D, was selected as = 0.152 m (6in). The height of the tower Ht is proportional to the efficiency of the tower. The higher the chimney is the better is the output. Ht = 2.1m was selected considering availability in the local market and ease of installation and support.

3. Experimental setup and data analysis
Firstly the open ground in front of tower-02 of MIST, Dhaka, Bangladesh was selected as the place for making the prototype considering the availability of sunlight and convenience of building the plant.

3.1. Experimental method
The outside temperature To was measured by pyrometer and these temperatures were noted down day wise. The temperature Ti inside the collector area was measured by pyrometer at the same time as the outside temperature and these temperatures were also noted day wise. The velocity of air at the entrance of the tower was measured by anemometer. The densities fo and fi were taken according to the corresponding temperatures To and Ti. (Appendix-4) The data was taken for different days of six different months and with by calculating those data, necessary results were found.

3.2. Equations and indentations
The output power of a solar updraft plant depends on several parameters (Table 1). The pressure difference between tower base and ambient is represented as,

$$\Delta P_{tot} = g \cdot (\rho_o - \rho_i) \cdot H_t$$

The output power can be calculated as,

$$P_{out} = \Delta P_{tot} \cdot v_t \cdot A_{coll}$$
Thus the total power available to the turbine can be calculated from this equation. As we used digital anemometer for measuring the air velocity at tower entrance it can also be calculated from this equation,

\[ v_t = \sqrt{2gH_t \left( \frac{T_t - T_o}{T_o} \right)} \]

And the collector area is calculated according to the geometrical structure (Table 2) of the collector

\[ A_{col} = \frac{1}{3} \pi r^2 h \]

**Table 1.** Nomenclature

| \( g \) | Gravitational acceleration (m/s^2) | \( D_c \) | Diameter of collector (m) |
|---|---|---|---|
| \( T_o \) | Ambient/Outside Temperature (°C) | \( A_{col} \) | Area of collector (m^2) |
| \( T_i \) | Temperature at tower entrance (°C) | \( D_t \) | Diameter of tower (m) |
| \( \rho_o \) | Outside air density(kg/m^3) | \( A_t \) | Area of tower (m^2) |
| \( \rho_i \) | Inside air density(kg/m^3) | \( \Delta P_{tot} \) | Total pressure difference(N/m^2) |
| \( H_t \) | Height of tower (m) | \( V_t \) | Air velocity at tower entrance (m/s) |

**Table 2.** Technical terms

| Tower height | 2.1m |
|---|---|
| Tower radius | 0.76m |
| Collector radius | 1.8283m |
| Min roof height (at center) | 0.2032m |
| Max roof height (at center) | 0.587m |
| Collector slope angle | 31.41° |
| Typical \( \Delta T \) | 10K |
| Average output | 20W |
| Tower material | PVC |
| Collector Material | PVC 0.9mm sheet |
| Plant frame and support material | Cast iron |

**Table 3.** (Data table)

| Month (2016) | Avg \( T_o \) (°C) | Avg \( T_i \) (°C) | Avg \( \rho \) (kg/m^3) | Avg \( \rho_i \) (kg/m^3) | Avg \( \Delta P_{tot} \) (N/m^2) | Avg \( V_t \) (m/s) | Avg \( P_{out} \) (Watt) |
|---|---|---|---|---|---|---|---|
| May | 32.9 | 50 | 1.1632 | 1.098 | 1.34 | 1.516 | 18.799 |
| June | 32.25 | 50.125 | 1.164 | 1.10225 | 1.3696 | 1.5525 | 19.767 |
| August | 32.8 | 50 | 1.163 | 1.09798 | 1.212 | 1.518 | 18.854 |
| September | 31.2 | 50 | 1.165 | 1.0796 | 1.6844 | 1.6988 | 26.506 |
| October | 32.4 | 52.78 | 1.1622 | 1.105 | 1.5564 | 1.6552 | 25.31 |
| November | 27.6 | 40.9 | 1.174 | 1.126 | 0.987 | 1.35 | 12.281 |
| December | 29.1 | 39.92 | 1.1672 | 1.1282 | 0.8028 | 1.214 | 8.977 |

4. Result and discussion

4.1. Graphs
Several data were collected at different times during a month (Table 3) (Figures 1-7). Average output during a month was calculated by averaging the data composed per day. From Figure 8 it is observed that highest power output is obtained between September and October and the lowest values of average power output is observed during November and December.
Temperature difference between inside and outside is directly correlated with the wind velocity at tower entrance [10]. The higher the temperature difference the higher wind velocity at tower entrance is observed (Figure 9). As the temperature of the trapped air inside the collector increases the density of air decreases and the hot air starts moving upwards with a certain velocity that depends on the temperature rise [11].

4.2. Prospect of solar updraft technology in Bangladesh
As Bangladesh is a semi-tropical country which is situated at North-eastern part of South Asia, receives abundant sunlight year round. In dry season the average bright sunshine duration is about 7.6hrs and in monsoon season the average bright sunshine is about 4.7hrs. The highest sunlight hours has been received in Khulna division which is 9.04hrs and second highest sunlight duration has been achieved in Barisal which is 8.75hrs.

Such amount of energy is greatly suitable for solar updraft technology to solve daytime energy crisis of the rural areas in Bangladesh. But to build a large scale solar updraft power plant Bangladesh will face some limitations as well. But those limitations can be eliminated if necessary and measured steps are taken by government.

5. Limitations and recommendations
Our main purpose was to observe and study the process of solar updraft principle, to do some analysis on structure and materials of components and also to estimate power generation of our pilot scale prototype. From this study and by comparing results with ideal systems we were able to find out our faults and drawbacks of the process we followed. The minimum height of the collector base from the ground level was higher than model-1 and caused cross or multidirectional air flow. When the air velocity was at a higher rate the air did not get enough time so that it could get trapped and get heated enough to move upwards rather it passed away through other sides of the collector. The ratio of collector diameter to tower diameter was small and the model would have been more effective if the ratio was in a larger range. We used PVC sheet as collector roof material which has a greater range of specific heat than that of glass. For the proper execution of “greenhouse effect” collector roof made of glass is highly recommended [12]. As this was our honors final year project we had limited resources in terms of finance and time. As we planned to introduce this model as a cost effective green technology, we had to execute this model at a very low budget so we were not actually able to modify this setup. We have started our project at the end of the summer so which hindered the potential of the project. Due to the unfavorable season we did not get expected amount of temperature difference on the other hand rainy or/and cloudy days of the winter has also affected the efficiency of the project.

6. Conclusion
Solar UpDraft power plant has many features that suggest this technology to be used in rural, remote and isolated communities. SUT provides steady power output which makes this technology suitable for smaller rural communities or for a small-scale industry. The power systems of developing
countries are not reliable on the other hand, small scale industries require continuous, uninterrupted power system and in this case, solar updraft power plant with heat storage system will provide the required continuous power output. In case of deserts and large wastelands solar updraft towers are most efficient at greater scale. Building solar updraft power plants could be more cost effective than building concentrated solar power plant. In that case the tower has to be built with local parts and local labor. The low maintenance requirement of SUT also ensures low cost of maintenance, which is a very important factor for constructing SUT’s at rural areas. The exceptional function of solar updraft collector for drying crops can be useful for many rural communities. Maintenance and repairing will only be an issue if there is lack of experienced technicians. In this case training programs should be held by government to train labors on maintaining the plant. During winter and monsoon seasons cloud coverage limits sunlight availability effecting overall production scheme. In this case heat storage methods and devices have to be implemented so that the continuous power generation scheme remains uninterrupted. Capacity of power generation of solar updraft tower depends on many factors like sun radiation, ambient temperature, humidity etc. but basing on these factors efficiency of SUTPP can be increased by increasing collector area and tower height proportionally. Rapid and accelerated growth of energy demand and shortage of energy could be a limiting factor of the economic development for developing countries. There are also negative environment externalities due to energy generation by conventional fossil-fuels. In this context, it has become quintessential to develop and promote alternative renewable energy sources that can lead to sustainable sourcing of energy. Renewable energy technologies can supplement the energy needs of developing countries to a significant level. Overall, for long term sustainable development integrated energy planning approach, upgraded government policies are necessary to support continuous development of energy generation technologies from renewable resources.

7. Appendix

Appendix 1. Computerized model of SUT

Appendix 2. Final model

Appendix 3. PVC sheet roof

Appendix 4. Density variation of air with respect to temperature.

8. References
[1] Schlaich J, Weinrebe G and Bergermann R 2013 Solar Updraft Towers. Solar Energy, Richter C, Lincot D, and Gueymard C A, Eds. New York, NY: Springer New York, p 658-687.
[2] Zhou X and Xu Y 2016 Solar updraft tower power generation. Solar Energy, 128, p 95.
[3] Zhou X, Bernardes M AD S and Ochieng R M 201 Influence of atmospheric cross flow on solar updraft tower inflow. Energy, 42(1), p 393-400.
[4] Ming T, Wang X, de Richter R K, Liu W, Wu T and Pan Y 2012 Numerical analysis on the influence of ambient crosswind on the performance of solar updraft power plant system. Renewable and Sustainable Energy Reviews, 16(8), p 5567-5583.
[5] dos Santos Bernardes M A and Zhou X 2013 Strategies for solar updraft tower power plants control subject to adverse solar radiance conditions. Solar Energy, 98, p 34-41.
[6] Zhou X, Yang J, Xiao B and Hou G 2007 Experimental study of temperature field in a solar chimney power setup. Applied Thermal Engineering, 27(11), p 2044-2050.
[7] Niroomand N and Amidpour M 2013 New combination of solar chimney for power generation and seawater desalination. Desalination and Water Treatment, 51(40-42), p 7401-7411.
[8] Ming T Z, Zheng Y, Liu C, Liu W and Pan Y 201. Simple analysis on thermal performance of solar chimney power generation systems. Journal of the Energy Institute, 83(1), p 6-11.
[9] Harte R, Höffer R, Krätzig W B, Mark P and Niemann H J, 2013. Solar updraft power plants: Engineering structures for sustainable energy generation. Engineering Structures, 56, p 1698-1706.
[10] Zhou X, Wang F and Ochieng R M 2010 A review of solar chimney power technology. Renewable and Sustainable Energy Reviews, 14(8), p 2315-2338.
[11] Kalogirou S A 2013 Solar energy engineering: processes and systems. Academic Press.
[12] Zhou X, Yang J, Xiao B and Hou G 2007 Experimental study of temperature field in a solar chimney power setup. Applied Thermal Engineering, 27(11), p 2044-2050.