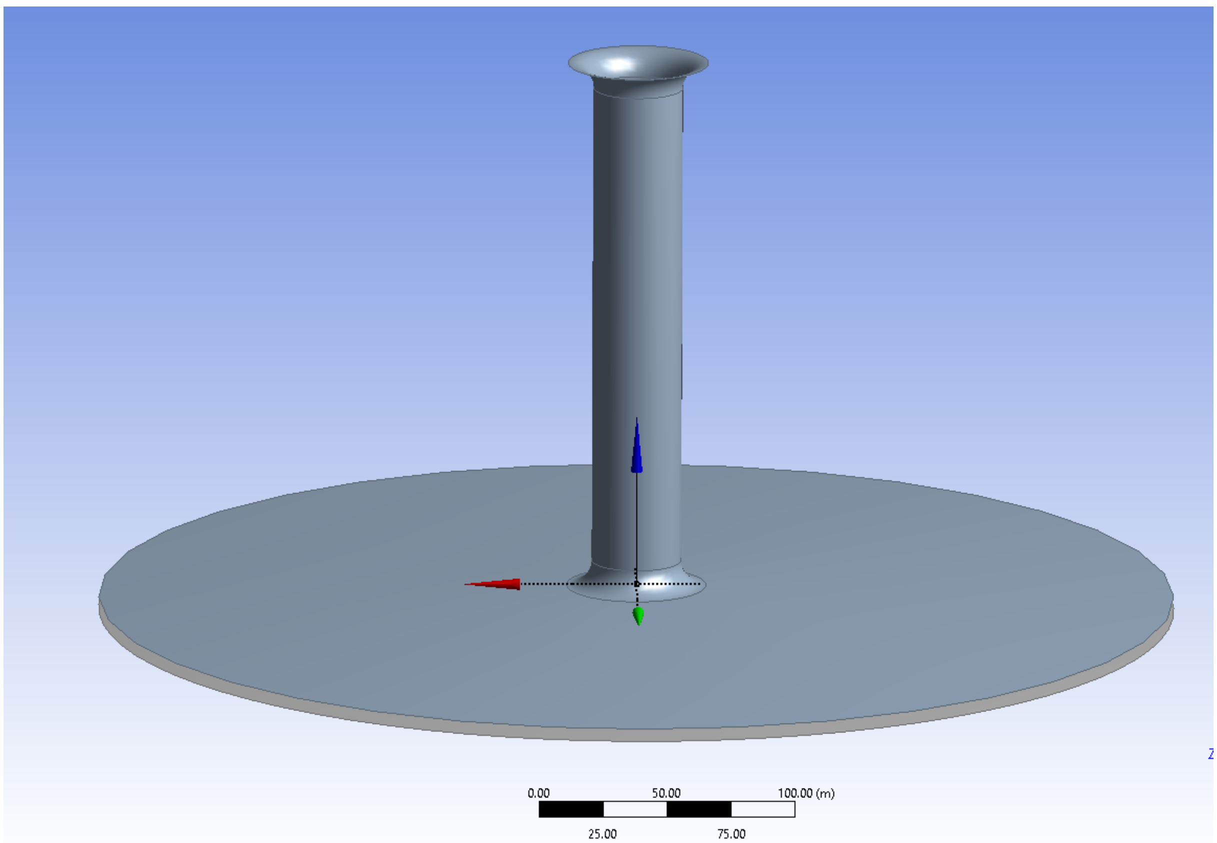
Research Proposal for Research Physics

Solar Updraft Tower Power Plant



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Executive Summary

Practical renewable energy may provide a sensible solution for the emerging fuel and energy shortage, and the problematic CO2 emissions.

The Solar Updraft Tower Power Plant (SUTPP) is a relatively new solar energy production technology that is yet to have been utilised with a full-scale operational unit.

SUTPP consists of a chimney, a turbine generator, and a solar air collector area - floored with a heat absorption plate.

The objective of our research is to investigate the dependence of the power plant performance on various constructive and operational parameters.

The analysis will be performed using the CFD (Computational Fluid Dynamics) code Star CCM+ belonging to Siemens.

The present work highlights the history of the concept as well as the reasons this concept is attractive.

A short simplified thermodynamics based model of the SUTPP is presented and solved. The results suggest that a reasonable power ($700[MW]$) can be obtained from one such device.

1 Motivation

Energy is the keystone of all life on earth, the primary source of which is the sun.

History has taught us that the more we learn to obtain and use this energy, the more human development is enabled and accelerated.

But clean, efficient, and cheap energy production is still being worked on. As of today, energy production all around the globe often falls short of local requirements, which results in frequent power outages.

As the world economy and population continue to rise, energy consumption is expected to go up with them.

Fossil fuel is limited and damaging to the environment and the humans within it; hence the utmost importance of alternative energy sources, especially solar, in meeting rising energy demands. Use of solar energy may also aid in solving a very big threat to human health - pollution.

Environmental pollution occurs when pollutants contaminate the natural surroundings. Pollution disrupts the fine balance of our ecosystem, affects our normal day-to-day lifestyles, and shortens our health spans.

Pollution is now peaking due to the development and modernization of many once rural areas. Contemporaneous with the improvements in science and technology, there has been a massive change in human potential. Entrapped by our own industrial and technological developments, air pollution threatens us on a personal daily basis - and is one of the most dangerous forms of pollution.

A biological, chemical, and physical alteration of the air occurs when smoke, dust, and any harmful gases and particles are introduced into the atmosphere, and make it difficult for all living beings to survive as their concentration increases and the air becomes more contaminated.

Burning of fossil fuels, for agriculture related activities, mining operations, exhaust from industries and factories, and household cleaning products entails air pollution. People release a huge number of chemical substances in the air every day. The effects of air pollution are alarming. It causes global warming, acid rains, respiratory and heart problems, and eutrophication. A lot of wildlife species are forced to change their habitat to survive.

Soil pollution occurs when the presence of pollutants, contaminants, and toxic chemicals in the soil is in high concentration that has negative effect on wildlife, plants, humans, and ground water. Industrial activity, waste disposal, agricultural activities, acid rain, and accidental oil spill are the main causes of soil pollution. This type of contamination influence health of humans, affects the growth of plants, decreases soil fertility, and changes the soil structure.

Water pollution can lead our world on a path of destruction. Water is one of the greatest natural resources of the whole humanity. Nothing will be able to live without water. However, we do not appreciate this gift of nature and pollute it without thinking. The key causes of the water pollution are industrial waste, mining activities, sewage and wastewater, accidental oil leakage, marine dumping, chemical pesticides, and fertilizers, burning of fossil fuels, animal waste, urban development, radioactive waste, and leakage from sewer lines. As a result, there is less water available for drinking, cooking, irrigating crops, and washing.

2 History

The first chimney turbine was depicted by Leonardo DeVinci as a smoke jack, and was illustrated by him 500 years ago. A gored animal could be rotated vertically above a fire or in an oven in a similar manner to popular dishes such as Shawarma and Döner Kebab.

Beginning in 1975, Robert E. Lucier applied for patents on a solar chimney electric power generator; between 1978 and 1981 patents (since expired) were granted in Australia,[1] Canada,[2] Israel,[3] and the US.[4]

In 1926 Prof Engineer Bernard Dubos proposed to the French Academy of Sciences the construction of a Solar Aero-Electric Power Plant in North Africa with its solar chimney on the slope of a large mountain.[5]

In 1982, a small-scale experimental model of a solar draft tower[6] was built in Manzanares, Ciudad Real, 150 km south of Madrid, Spain. The power plant operated for approximately eight years. The tower's guy-wires were not protected against corrosion and failed due to rust and storm winds. The tower blew over and was decommissioned in 1989.[7]

The solar tower was built of iron plating only 1.25 millimetres thick. The chimney had a height of 195 metres and a diameter of 10 metres with a collection area (greenhouse) of 46 hectares (110 acres) and a diameter of 244 metres (801 ft), obtaining a maximum power output of about 50 kW. Various materials were used for testing, such as single or double glazing or plastic (which turned out not to be durable enough). During its operation, 180 sensors measured inside and outside temperature, humidity and wind speed data was collected on a second-by-second basis.[8]

In December 2010, a tower in Jinshawan in Inner Mongolia, China, started operation, producing 200 kilowatts.[9] The 1.38 billion RMB (USD 208 million) project was started in May 2009. It was intended to cover 277 hectares (680 acres) and produce 27.5 MW by 2013, but had to be scaled back. The solar chimney plant was expected to improve the climate by covering loose sand, restraining sandstorms.[10] Critics have said that the 50m tall tower is too short to work properly and that it was a mistake to use glass in metal frames for the collector, as many of them cracked and shattered in the heat.[11]

In mid-2008, the Namibian government approved a proposal for the construction of a

400 MW solar chimney called the 'Greentower'. The tower is planned to be 1.5 kilometres (4,900 ft) tall and 280 metres (920 ft) in diameter, and the base will consist of a 37 square kilometres (14 sq mi) greenhouse in which cash crops can be grown.[12]

In Xian, central China, a 60-metre urban chimney with a surrounding collector has significantly reduced urban air pollution. This demonstration project was led by Cao Junji, a chemist at the Chinese Academy of Sciences' Key Laboratory of Aerosol Chemistry and Physics.[13]

3 Mathematical Analysis

In this section, we will estimate the energetic output of the SUTPP. In order to do so, we will calculate the pressure inside the tower and outside it, and use Bernoulli's equation to calculate the flow velocity and the kinetic energy of the stream entering the wind turbines at the upper end of the tower.

3.1 Geometric Configuration

Consider an axisymmetric tower – Fig. (1) of height h and diameter d whose lower base is heated to temperature T_h (by means of a large solar energy capturing device). Turbines will be placed at the upper base of the tower.

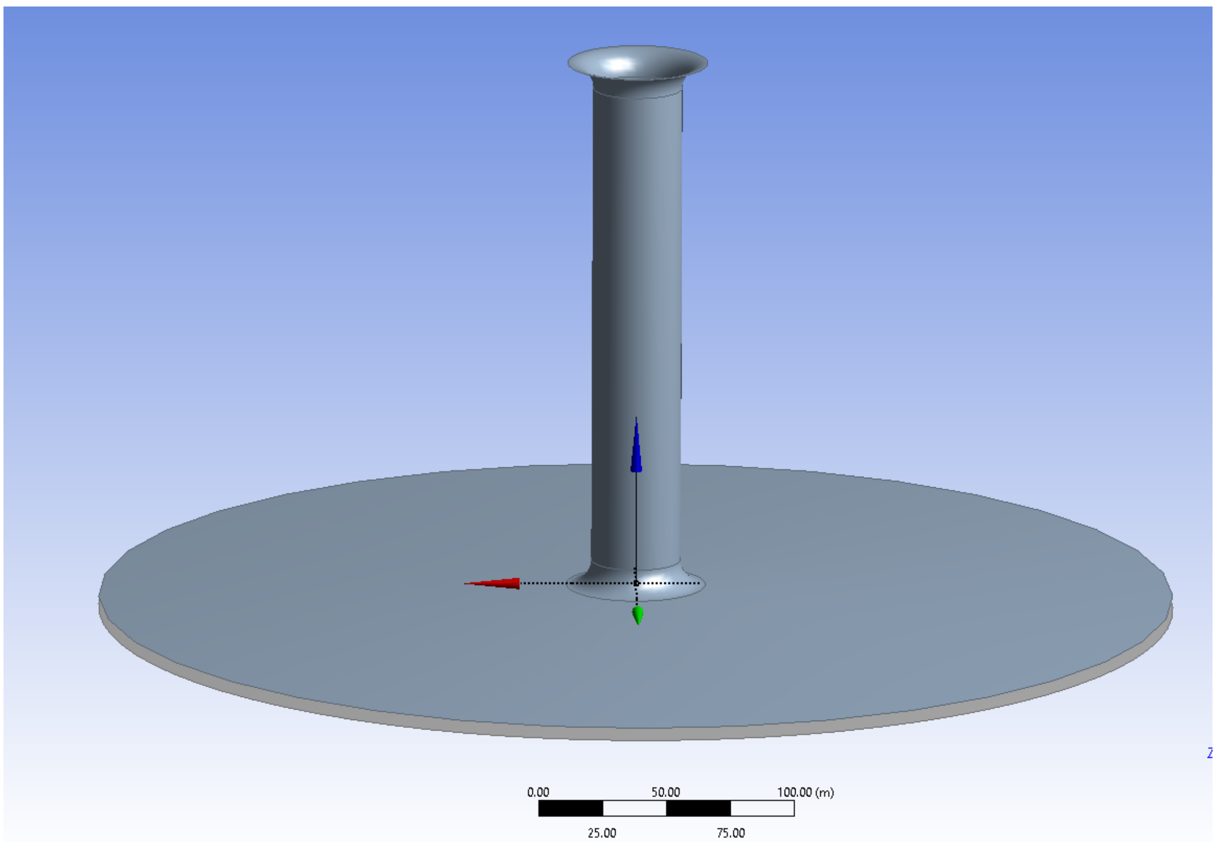

Figure 1: Geometric Layout of the tower

3.2 Atmospheric pressure and temperature distribution

Temperature, pressure and density are distributed along height in the free atmosphere according to what is called "adiabatic distribution".

3.2.1 Temperature distribution with height

The atmospheric adiabatic temperature distribution with height is linear, given by:

$$T = T_h - \frac{g}{c_p} \cdot z \tag{1}$$

Where the slope of the graph is called "atmospheric lapse rate":

$$\Gamma = \frac{g}{c_p} \left[\frac{K}{m}\right] \tag{2}$$

We observe that Γ is approximately $9.8 \left[\frac{K}{km}\right]$.

3.2.2 Pressure distribution with height

The pressure as a function of height (z) given by the equation:

$$p = p_0 - \int_0^z p \cdot g \cdot \mathrm{d}z \tag{3}$$

Accounting for the fact that the pressure, p, must also obey the ideal gas law and also accounting for Eq.(1), we have:

$$p_0 - \int_0^z p \cdot g \cdot \mathrm{d}z = \rho \cdot R \cdot T_h \cdot \left(1 - \frac{g}{c_p \cdot T_h} \cdot z\right) \tag{4}$$

Differentiating Eq. (4), we obtain:

$$-\rho \cdot g = R \cdot T_h \cdot \left(1 - \frac{g}{c_p \cdot T_h} \cdot z\right) \cdot \frac{\mathrm{d}\rho}{\mathrm{d}z} - \rho \cdot R \cdot \frac{g}{c_p} \tag{5}$$

Accounting for:

$$
\begin{cases} c_p - c_v = R \\ \frac{c_p}{c_v} = k \end{cases} \tag{6}
$$

where k is the adiabatic index (1.4 for air which has a diatomic molecule) in Eq. (5) and regrouping the terms, we obtain:

$$
-\frac{1}{k} \cdot \rho \cdot g = R \cdot T_h \cdot \left(1 - \frac{g}{c_p \cdot T_h} \cdot z\right) \tag{7}
$$

We can re-write Eq. (7) as:

$$
\frac{\mathrm{d}\rho}{\rho} = -\frac{1}{k} \cdot \frac{g}{R \cdot T_h \cdot \left(1 - \frac{g}{c_p \cdot T_h} \cdot z\right)} \cdot \mathrm{d}z \tag{8}
$$

Integrating Eq. (8), we obtain:

$$
\rho = \rho_h \cdot \left(1 - \frac{g}{c_p \cdot T_h} \cdot z\right)^{\frac{1}{k-1}} \tag{9}
$$

Where index "h" signifies "Hot" - and is the density at ground level inside the tower.

Using the ideal gas law and accounting for Eqs. (1) and (9), we obtain the pressure distribution as:

$$
p = \rho_h \cdot R \cdot T_h \cdot \left(1 - \frac{g}{c_p \cdot T_h} \cdot z\right)^{\frac{k}{k-1}} \tag{10}
$$

Pressure and temperature distribution outside the tower can be obtained by Eqs. (1) and (10) by simply substituting the index h for index 0, representing conditions on the ground outside the tower.

3.3 Pressure difference between inside and outside the tower at upper base

We will use the ideal gas law to determine the density inside the tower, assuming that the pressure is the atmospheric pressure at ground level

$$\rho_h = \frac{p_0}{R \cdot T_h} \tag{11}$$

Where index h signifies inside the tower (Hot) and index 0 signifies in the free atmosphere outside the tower.

We will assume the following numerical data:

- Height of the tower: $h = 200[m]$
- Diameter of the tower: $d = 35[m]$
- Outside temperature: $20°C$
- Inside temperature: $60°C$

From the ideal gas law, we obtain:

$$\rho_0 = \frac{p_0}{R \cdot T_0} = \frac{101325}{287 \cdot 293} = 1.205 \left[\frac{kg}{m^3}\right] \tag{12}$$

Using Eq. (9), we obtain:

$$\rho_h = \frac{101325}{287 \cdot 333} = 1.06 \left[\frac{kg}{m^3}\right] \tag{13}$$

Using Eq. (12) in Eq.(10) we obtain the outside pressure as:

$$p_{outside} = 1.205 \cdot 287 \cdot 293 \cdot \left(1 - \frac{9.8 \cdot 200}{1004 \cdot 333}\right)^{\frac{1.4}{1.4-1}} = 98,986[Pa] \tag{14}$$

Using Eq. (13) in Eq. (10) we obtain the inside pressure as:

$$p_{inside} = 1.06 \cdot 287 \cdot 333 \cdot \left(1 - \frac{9.8 \cdot 200}{1004 \cdot 333}\right)^{\frac{1.4}{1.4-1}} = 99,242[Pa] \tag{15}$$

From Eq. (14) and Eq. (15) we obtain the pressure difference at the top of the tower as:

$$\Delta p = 99242 - 98986 = 256[Pa] \tag{16}$$

3.4 Flow rate from inside to outside the tower

Using Bernoulli's law, we have the flow velocity as:

$$v = \sqrt{\frac{\Delta p \cdot 2}{\rho}} = \sqrt{\frac{256 \cdot 2}{1.06}} = 10.3 \left[\frac{m}{s}\right] \tag{17}$$

3.5 Power output

The gross power output or power output potential is given by:

$$P = \Delta p \cdot \dot{V} \tag{18}$$

Where $\dot{V}$ is the volumetric flow rate, given by:

$$\dot{V} = A \cdot v = \frac{\pi \cdot d^2}{4} \cdot v \tag{19}$$

Using (16) and (17) in Eq. (18) with the help of Eq. (19), we obtain:

$$P = 256 \cdot \frac{\pi \cdot 35^2}{4} \cdot 10.3 = 2,536,898[W] = 2.54[GW] \tag{20}$$

Of course, it is impossible to utilise all of the power potential given in Eq. (20). We transform this power potential in electric power by means of a wind turbine.
The typical efficiency of a shrouded wind turbine is of the order of magnitude:

$$\eta = 30\% \tag{21}$$

Therefore, we have a power output of:

$$P_{electric} = P \cdot \eta = 762[MW] \tag{22}$$

Just for comparisons sake, one of the coal power stations at Hadera has an installed power output of 650 MW, so this device might be equivalent to a conventional power station, without the fuel costs since sun power is free.

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