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PROSPECTS OF INCLINED SOLAR CHIMNEY CONCEPT IN SOUTH AFRICA

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ABSTRACT

Solar Chimney also known as Solar Updraft Power Plant concept is successfully proven in the last few decades through many experimental and theoretical approaches. The present concept of solar chimney requires construction of a tall vertical chimney at the center of a large area, known as the collector. Construction of a tall chimney creates questions about its stability and demands elaborated engineering techniques while constructing it. The high investment cost compared to the plant efficiency and the limited heights of the chimney due to the technological constraints are considered the main disadvantages of the solar chimney plant. In order to overcome these problems, many novel concepts were proposed; One being the Inclined Solar Chimney Power Plant (ISC). ISC which is constructed along the face of a high rising mountain, on which maximum solar insolation is incident throughout the year. The chimney and the collector get merged here. This makes the structure stable, cost effective and easy for construction. The base of a mountain acting as a collector can be used further for water heating and drying agricultural products. Application of such solar technologies are very relevant for South Africa because nation experience some of the highest levels of solar radiation in the world and this renewable resource holds great potential for the country. In this paper we will analyze and discuss the concept of inclined solar chimney and its prospects in South Africa, considering country's solar resource.

INTRODUCTION

The global energy consumption has increased tremendously in last few decades and to supply this increased energy demand many new power plants are built or being built, mainly of fossil fuel. But continuing utilization of fossil fuels is creating many challenges especially air pollution, climate change, global warming. These facts lead the researchers and governments around the world to focus more on the development and implementation of renewable energy. Of all the renewable energy sources, solar energy alone has potential to supply world's all energy demand and therefore can be considered as the future human energy resource. Electricity can be generated from solar energy through two paths, the photovoltaic effect and the solar thermal cycle. The solar chimney or solar updraft power plant (SUPP) is one of the solar thermal plants that can operate and produce electricity with very low temperature difference (starting with 10 ^{o}C [1]).

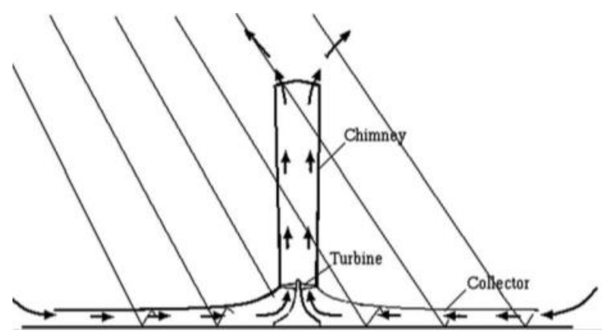

Figure 1: Schematic of the solar chimney

The concept of solar chimney was first suggested by Günther in 1931 and again by Schlaich in 1978. The basic concept is that a tall vertical chimney is constructed at the centre of a large horizontal land area covered with transparent roof of glass or plastic (Figure. 1). The transparent roof is separated from the ground by some distance, typically a few meters, and is sloped upwards towards the base of the chimney at the centre. Its physical operating principle is very simple. Solar radiation heats air underneath the transparent roof by means of greenhouse effect. When air gets hot, the density is reduced and the air is driven naturally up to the chimney outlet under the natural buoyancy effect. This generates an updraft air velocity in the chimney that operates the turbine, which is located at the chimney base, to generate electricity. New air will enter the system through the periphery of the solar collector and it will be heated and the process will continue.

To prove this concept a prototype of a solar chimney was constructed with a height of 194.6 m and collector area of radius 122 m at Manzanares, Spain. Data of actual working of the solar chimney was collected. Schlaich reported the nominal electric power output at Manzanares to be 50 kW [1].

Figure 2: Solar chimney prototype at Manzanares

Subsequently, some more solar chimney prototypes were studied with heights ranging from 2 m to 10 m and the collector areas ranging from about 6 m^2 to about 100 m^2. One such example will be a courtyard solar chimney built by Krisst, which was 10 m tall and with collector area of about 100 m^2. Its nominal power output was 10 W [2]. Another chimney constructed by Kulunk in Turkey was 2 m in height and had collector area of 9 m^2 and its power output was 0.14 W [3]. However, no other actual power plant deploying solar chimney has been constructed after Manzanares and tested.

The concept of solar chimney is particularly attractive because of its simplicity of working. Though the concept has been explored by some researchers for drying of food crops or for ventilation of dwellings [4–6], its main advantage is that it converts solar energy directly into mechanical energy of air draft without needing any complex mechanism and without requiring continuous supply of water, or any special materials.

LIMITATION OF SOLAR CHIMNEY

The concept of solar chimney has many disadvantages and limitations. The main limitation is the low efficiency which is lower than 1%. Efficiency of solar chimney increases as per the square root of the chimney height [1]. The chimney height, therefore, in any solar chimney power plant must be as high as possible. But increase in the chimney height beyond a limit would be counterproductive. This is because, air cools while raising through chimney and beyond a certain height its density equals or exceeds the density of ambient air at that height [12].

A substantial capital cost has to be incurred for constructing the chimney. The cost analysis was carried out by Schlaich [1] and by Schlaich et al. [7] and by Bernardes [8]. They considered power plants of capacity 100MW and the chimney heights of 950 m, 1000 m, and 850 m, respectively. The total investment costs were estimated to be 300.0 M€, 402.0 M€ and 352.4 M€, respectively, in which the costs of constructing chimney were 22.7%, 38.9% and 18.3% respectively. Fluri et al. [9] carried out a more detailed analysis in 2009. They found that the total investment costs would be much higher than those reported earlier. For a 100MW unit with chimney height of 1000 m the revised investment was estimated to be 668 M€, where chimney cost was 22%. Further, for 100MW unit, with chimney height of 850 m, it is 792 M€, of which the chimney cost is 14%. It may be noted at this stage that the cost of conventional thermal power plant is approximately 80 M€ for 100MW capacity.

Apart from the economical consideration, tall vertical chimneys have problems of stability especially in the event of stormy winds or even a mild earth-quake tremor. Further, engineering challenges involved would nullify the advantages of simplicity of operation. It is worth noting in this context, that an ambitious project of solar chimney power plant of 200MW in Australia [10] has been down sized to 50 MW, reducing the proposed chimney height from 1000 m to 480 m [11].

In order to overcome the difficulties of stability and costs of tall solar chimneys, many researchers have suggested some novel and unconventional concepts. Zhou et al. suggested [12] that a hole can be excavated at the centre of a high rising mountain, which will act as the chimney. The collector area would be spread around the mountain. Though the cost reduction may not be much in this concept, the problems of stability of a tall chimney is taken care of.

For a 100MW plant at 1 km elevation mountain with 19.3 km2 collector area and solar insolation 2300 kW h m^{-2} a^{-1}, the cost was estimated to be 646.9 M€ of which the cost of chimney was 78%. However, the life of such a chimney is expected to be much longer, as against that of a concrete chimney being 25–30 years. Hence it would also be cost effective in the long run. Another concept of 'floating solar chimney' has been suggested by Papageorgiou [13]. Here the chimney is not made of concrete, but of a flexible material and floats on air with the help of a lighter gas like helium. The chimney essentially has a heavy base and the walls are filled with a lighter gas. The support rings allow air to enter and pass through them freely, so that the chimney does not yield under wind pressure. These features minimize the problems of safety and heavy investment cost.

The economic analysis of power plant using floating solar chimney has been carried out by Zhou et al. [14]. They have estimated the total investment for a 100MW plant to be 325.5 M€ of which 24.2% is the cost of flexible solar chimney. The life of chimney, however, is relatively short (about 15 years) which means higher capital cost on the annualized basis.

THE CONCEPT OF INCLINED SOLAR CHIMNEY

The practical feasibility of the unconventional and novel concepts discussed earlier for constructing stable and economical high rising solar chimneys may be debatable, but the attempts of various researchers in this direction underline the fact that, in order to make the promising concept of solar chimney cost competitive and technologically realistic, the issue of construction of high rising chimneys needs to be addressed.

Panse et al.[15] introduced another concept for the construction of a solar chimney, which would involve less cost, would have relatively less problems of safety and has a practical feasibility. In order to construct a solar chimney with sufficient height, with reliable stability and with low cost, the concept being discussed here is that of an Inclined Solar Chimney (ISC) for power production. Inclined solar chimney is constructed along the face of a high rising hill from its bottom to the top. Many geographical locations exist in all parts of the world, where heights of hills from bottom to top are 500 m or more. Solar chimneys of corresponding heights can be constructed at such locations with high stability and without a heavy cost. The idea of making use of hills for enhancing the heights of solar chimneys by constructing vertical chimney on top of a hill; or for improving the efficiency of collector area is also found in the literature. This basic concept first explored by Bilgen [16], is that the face of a hill facing the Sun for major part of the year and inclined appropriately, as per the latitude of the place would act as the collector area. He has analysed the efficiency of collector under these conditions. In the present concept discussed here, inclined face of the mountain itself acts as the chimney as well as the solar energy collector and the flow of air in this inclined chimney is being studied.

The inclined solar chimney differs from the vertical solar chimney essentially in three aspects:

(1) The collector area in ISC is not horizontal and separated from the chimney. The collector area is the inclined face itself of the hill, where the chimney is constructed. Depending upon the latitude of the location, the inclined face of the hill is so chosen that it receives maximum solar insolation over the year. For example, surfaces facing north with an angle of inclination of about 40^0 is efficient for locations in Western Cape.

(2) The chimney in ISC is not cylindrical in shape, nor is it of a smaller cross-section area than the collector, as is the case in a vertical chimney. The so called ‘chimney’ here is the inclined face of a hill, which may extend a few hundred meters in length and in width. This area is covered with a transparent roof, separated from the ground at an appropriate distance (typically a few meters). For better results, the ground may be covered with an inexpensive non-conducting material, black in colour. The air trapped between the floor and the transparent roof becomes hot and lighter on receiving solar radiation and starts moving up the hill and emerges from the outlet of the chimney at the top of the hill with significant kinetic energy. Cold air rushes into the inlet at the foot of the hill.

(3) In a vertical solar chimney, the mass of air in the collector area gets heated and attains a lower density before entering the chimney; and a turbine is used at the base of the chimney. Further, it is difficult to position any turbine at the top of a high vertical chimney. In the case of ISC, on the other hand, the inlet of the ‘chimney’ is the same as the inlet of the collector and the air gets heated while it is rising through the chimney. The turbine may, therefore, be conveniently positioned at the top of the mountain near the outlet of the chimney. Also, unlike a vertical chimney, the temperature of air progressively increases; and its density progressively decreases along the length of the chimney.

These aspects which sets the inclined solar chimney different from the traditional solar chimney, makes ISC cost effective and stable with a large height.

ISC PROSPECTS IN SOUTH AFRICA

Coal is the most polluting energy resource on the planet, and the main cause of the world’s CO_2 emissions [17]. South Africa is the world’s fifth largest producer, and is already the sixth largest consumer of coal. [18] In South Africa, energy provision is dominated by fossil fuels, particularly coal (around 72% of primary energy and 94 % of electricity generated) and therefore the carbon emission is high in the country. In a year South Africa consume over 123.8 million tons of oil equivalents for various uses [19]. As one of the leading carbon emitting nations in the world, South Africa need to increase the renewable energy content, specially solar energy, within the national energy production which will help reduce GHG emissions from the country.

Solar energy is also relevant for South Africa because the country experiences some of the highest levels of solar radiation in the world and this renewable resource holds great potential for the country. South Africa’s daily solar radiation varies between 4.5 and 6.5 kWh/m2 which is higher than the levels found in the United States (3.6 kWh/m2) and those found in Europe (2.5 kWh/m2), which are two regions of the world where solar technology has been extensively deployed [20]. Figure 3 below shows the annual solar radiation (direct and global) for South Africa, which reveals very high solar resource potential for solar water heating applications, solar photovoltaic and solar thermal power generation.

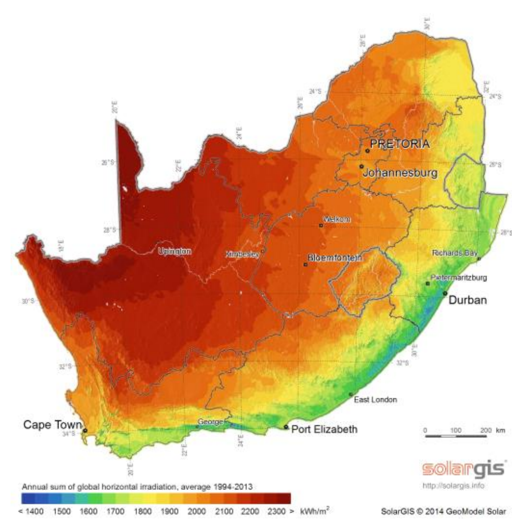

Figure 3a: Annual global solar radiation of South Africa

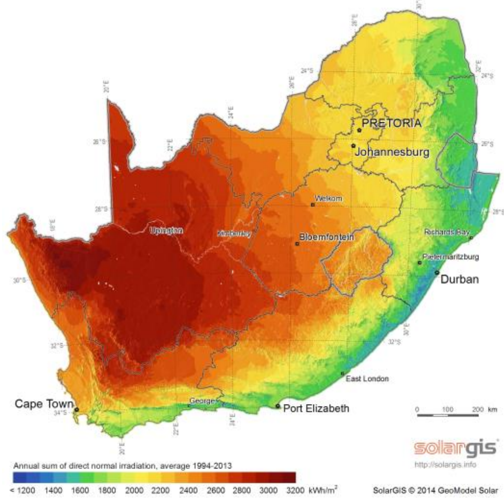

Figure 3b: Annual direct solar radiation of South Africa

Fluri, also investigated the Direct Normal Irradiance (DNI) solar radiation resources for South Africa. Analysis of this resource shows that there is huge potential for solar thermal technologies in South Africa and the potential concentrated solar power electricity generation capacity was calculated to be 547.6 GW [21]. South Africa boasts an area of roughly 194,000 km2 where extremely high levels of radiation exists, with the Northern Cape region offering one of the best solar resources in the world. The daily duration of sunshine is also high.

To utilize this abundance amount of solar radiation in inclined solar chimney, we need mountains and hills which have slopes facing towards north. Unlike most of Africa, the perimeter of South Africa's inland plateau rises abruptly to form a series of mountain ranges before dropping to sea level. These mountains, known as the Great Escarpment, vary between 2,000 meters and 3,300 meters in elevation.

Peak Name	Location	Height in meter
Mafadi	Lesotho	3,450
Injasuti	Lesotho	3,410
Ntheleli	Lesotho	3,405
Lithobolong	KwaZulu Natal	3,375
Trojan Wall	KwaZulu Natal	3,354
Red Wall	KwaZulu Natal	3,337
Khoko-Ntso	KwaZuluNatal	3,331
Ship's Prow	KwaZuluNatal	3,325
Nkosazana	KwaZuluNatal	3,318
Champagne Castle Ridge Peak	KwaZuluNatal	3,318

Table 1: Highest mountains in South Africa [22]

Table 1 shows the list of highest mountains in South Africa, the top ten mountains listed has height of more than 3000 m. There are around 5173 peaks in South Africa [22]. Even if 25 % of these peaks have slope facing north, then with such great solar resource, south Africa will be a great place to peruse further development and implementation of inclined solar chimney concept.

CONCLUSION

In the inclined solar chimney concept, chimney and collector area merges and the chimney is constructed along the face of a high rising hill, which receives maximum solar insolation over the year. Because of this, inclined solar chimney would be cost effective and stable with a large height compared to solar chimney. The density of air inside the chimney progressively decreases along the length of the chimney and hence its velocity at the outlet end is greater than that at the inlet end. Wind velocities at the top of the hill enhance the velocity of the emerging air draft. Thus, ISC is capable of harnessing both the solar and the wind energies. The dimensions of the chimney decide the temperatures attained by the emerging air draft and its kinetic energy. Apart from power output, the ISC would also give rise to a hot air draft emerging from the outlet of the chimney at the top of the mountain. It can be used for drying of agricultural products and bio-mass, which is an additional advantage.

Considering South Africa’s very high solar radiations level and its geographical structure with around 5000 peaks and mountains, inclined solar chimney can be implemented successfully here. Further development work is necessary with actual experimentation and CFD modelling.

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