State and Recent Advances in Research and Design of Solar Chimney Power Plant Technology

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Kurzfassung

Forschungs- und Entwicklungsstand beim Entwurf solarer Aufwindkraftwerke

In solaren Aufwindkraftwerken erwärmt die Sonneneinstrahlung in Kollektoren die darin befindliche Luft, die über zentrale Abluftkamine in große Höhen abströmt. Dieser Massenstrom treibt druckgestufte Turbinen am Kaminfuß, deren angekoppelte Generatoren Strom erzeugen. Über keinen anderen Typ von Solarkraftwerken sind so irreführende, oft falsche Aussagen in Umlauf, die zumeist auf betriebliche Fehlinterpretationen des unter der Leitung von J. Schlaich 1982 in Manzanares errichteten 50 kW-Prototyp zurückgehen. Der vorliegende Beitrag skizziert einige der seither erzielten großen Fortschritte in Forschung und Entwicklung dieser für den Einsatz in ariden Gebieten vielversprechenden Stromerzeugungs-Technologie. Er erläutert die flexiblen Steuerungsmöglichkeiten der Leistungsabgabe, gibt einen Überblick über die durch moderne Hochleistungsbetone und Tragwerksforschung beim Bau von Naturzugkühltürmen konzipierten wirtschaftlichen Bauweisen und weist auf den Entwicklungstand besonders leistungsstarker Turbinen für diesen Kraftwerkstyp hin.

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History and General Working Concept

Although fossil-fuelled power plants will be built for many more years, renewable energy sources will play an ever increasing role. One of the available concepts is solar chimney power plants which imitate the daily solar-driven up- and downdraft in the lower atmosphere and convert parts of the energies therein into electric power.

The general working concept is illustrated in Figure 1. A solar chimney power plant (SCPP) consists of the collector area (CA), the turbine(s) with coupled generator(s) as power conversion unit (PCU), and the solar chimney (SC). In the CA, a large glass-covered area, wide-banded solar radiation heats the collector ground and consequently warms up the air inside the CA, which streams towards the centre of the collector. There, in the PCU, the energy in the stream of warm air is partly transformed into electric power. For increased effectiveness, a pressure sink at the PCU outlet is created by the huge solar chimney.

Solar chimney power plants are the most sustainable natural resources for electric power generation. During service, they are completely free of carbon dioxide emissions, since they use solar radiation as fuel. If one incorporates all energies required for plant construction in an energy balance measured by CO_2 emissions, one ends up with around 10 g of CO_2 per kWh of produced electricity, depending on the service-life duration of the plant. Intended designed service lives are 80 to 120 years, admitting renewals of the turbo-generators and parts of the glass-roof.

Such power station concepts, however, will only deliver sufficient efficiency in areas with high solar radiation input of more than 2.0 MWh/a, as valid in all great deserts up to 30° latitude north and south of the equator. The degree of efficiency of a SCPP then depends primarily on the size of the CA (air temperature) and on the height of the SC (pressure difference) [23]: A plant with CA diameter of 7 000 m and with SC height of 1 500 m is estimated to deliver a maximum electric power of 400 MW, on mid-days in summer time.

This solar updraft power generation was first proposed in 1903 by the Spanish engineer *I. Cabanyes* [5]. Another early description can be found in the work [11] of the German author *H. Günther* from 1931. Around 1975, a series of patents were granted to the US engineer *R.E. Lucier* in countries with deserts suitable for SCPPs, like Australia, Israel and the US.

Starting in 1982, a team led by the German civil engineer *J. Schlaich* took the initiative and constructed a prototype SCPP in Manzanares/Spain, with a 200 m high SC and a maximum power output of 50 kW. This plant operated successfully for more than six years. Figure 2 gives an impression of this prototype plant. In 1987, *Pasumarthi* and *Sherif* erected a smaller prototype installation in California and published the first thermo-mechanical plant model [18]. Since those days, projects for SCPPs have been developed in arid zones all over the world, but none of them has been brought to realisation, up to now.

The prototype plant in Figure 2 contained a single PCU with vertical turbine axis. Such solutions have been considered also for bigger plants, but modern designs show a series of single CPUs with horizontal axes around the tower foot perimeter, an arrangement more advantageous for turbine installation, control, and maintenance, and - last but not least - cost of energy output.

The present publication will focus on actual research and development recognition of SCPPs, which have been gained partly by large-scale experiments and mainly by computer simulation. General aspects of these power plants are summarised in [27], including a discussion of their pros and cons. A recent compilation of SCPPs can be found in [22], and the basic source about this power generation from the 1990's is [23]. The principal question of experts as well as laymen, namely if a tower of height more than 1000 m can be built at all, has considerably calmed down since the Burj Dubai Skyscraper in the Arabian Emirates of 818 m of height is under construction.

Thermal Design and Simulation of Air Flux and Energy Output

SCPP Working Principle: Conversion from Solar Energy to Electricity

Direct and diffuse solar irradiation strikes the glass collector roof of the CA, where specific

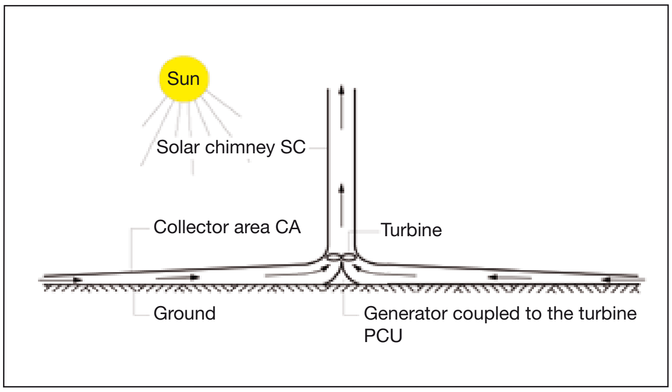

Figure 1. Schematic solar upwind power plant.

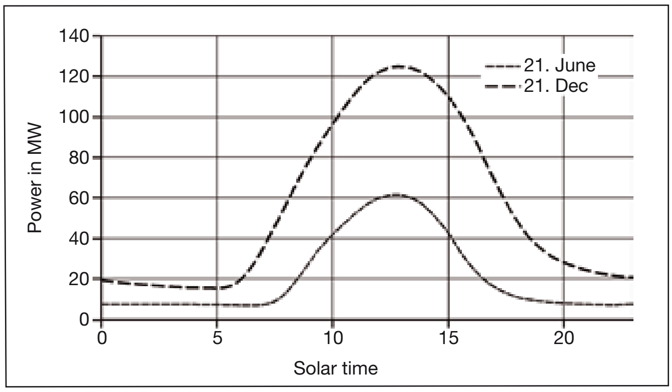

Figure 3. Electrical power output of SCPP for 24 hours during summer and winter.

fractions of the energy are reflected, absorbed and transmitted. The quantities of these fractions depend on the solar incidence angle and optical characteristics of the glass, such as the refractive index, thickness and extinction coefficient. The transmitted solar radiation strikes the ground surface of the CA below the roof, thereby heating it. At the ground surface, a part of the energy is absorbed while another part is reflected back to the roof, where it is again reflected to the ground. The multiple reflection of radiation continues, resulting in a higher fraction of energy absorbed by the ground, known as the transmittance-absorptance product of the ground. Through the mechanism of natural convection, the warm ground surface heats the adjacent air, causing it to rise. The buoyant air rises up into the chimney of the plant, thereby drawing in more air at the collector perimeter and thus initiating forced convection which heats the collector air more rapidly. Through mixed convection, the warm collector air also heats the underside of the collector roof. Some of the energy absorbed by the ground surface is conducted to the cooler earth below, while radiation exchange also takes place between the warm ground surface and the cooler collector roof. In turn, via natural and forced convection, the collector roof transfers energy from its surface to the ambient air adjacent to it. Radiation exchange also takes place between the collector roof and the sky which can be reduced by glass surface coating.

Figure 2. J. Schlaich's prototype SCPP from 1982 at Manzanares/Spain.

As the air flows from the collector perimeter towards the chimney its temperature increases while the velocity of the air stays approximately constant because of the increasing collector height [16, 20]. Due to the decrease in frontal area when entering the chimney, the air velocity increases and again remains approximately constant until it exits the chimney. A temperature drop is experienced across the turbine(s), while within the chimney the temperature decreases with height at a rate approximately equal to the dry adiabatic lapse rate.

The driving force or potential that causes air to flow through the solar chimney power plant is due to the pressure difference between a column of cold air outside and a column of hot air inside the chimney. However, certain pressure losses are experienced as the air flows through the system. As the air moves into the collector from an essentially stagnant condition, it experiences a pressure drop. Under the collector roof, the roof and ground surfaces exert a frictional force while the collector roof supports exert a drag force on the flowing air, thereby causing a further pressure drop. At the turbine inlet, the decreasing flow area causes another pressure drop. A pressure drop is experienced as the turbine(s) extract energy from the flowing air, while in the chimney the internal wall friction and possible supporting bracing structures (spokes) cause a minor pressure drop over the height of the chimney. The air exiting the chimney experiences a pressure differential due to the shape of the chimney outlet and a loss in kinetic energy which results in a dynamic pressure drop.

As the collector air flows across the turbine(s), the kinetic energy of the air turns the turbine blades which in turn drive the generator(s).

Numerical Model and Computer Simulation

Conservation of mass, momentum and energy equations for the collector and chimney air, as well as energy balance for the collector roof and ground form the basis of the numerical model [16, 20]. A draught equation calculates the pressure drop across the turbine by determining the driving potential pressure and subtracting all the pressure losses throughout the system from it. Convective and radiative heat transfer equations calculate all the relevant energy transfers from solar radiation to the energy ultimately absorbed by the collector air. Momentum equations are employed to ascertain the various friction and drag forces imposed on the flowing air.

Relevant conservation equations to determine the thermo-flow field throughout the solar chimney power plant are derived and discretised using finite difference (element) approximations. Ambient meteorological conditions for a reference plant site (near Sishen, South Africa) are used as model input. The equations are solved simultaneously by computer simulation employing standard Visual Basic 6.0 code leading to the results presented in the next sub-chapter. The performance of the solar chimney power plant is ascertained by determining the mass flow rate through the system that will maximise the power output of the plant at a particular time.

This simulation concept is explained in great detail in [20].

Simulation Results: Power Output and Control Possibilities

Figure 3 illustrates the typical daily power output profile during summer and winter for a large-scale solar chimney power plant [19], with main dimensions of a 5000 m collector diameter and a 1000 m high chimney with 210 m inside diameter. No control is involved over the power generated by the plant and therefore it simply produces the maximum power at each moment in time, as determined by the prevailing ambient conditions.

A sensitivity analysis on the influence of various operating and technical plant specifications [21] revealed that the treatment of the top surface of the collector roof to reduce its reflectance or emissivity can potentially mean major enhancements in solar chimney power

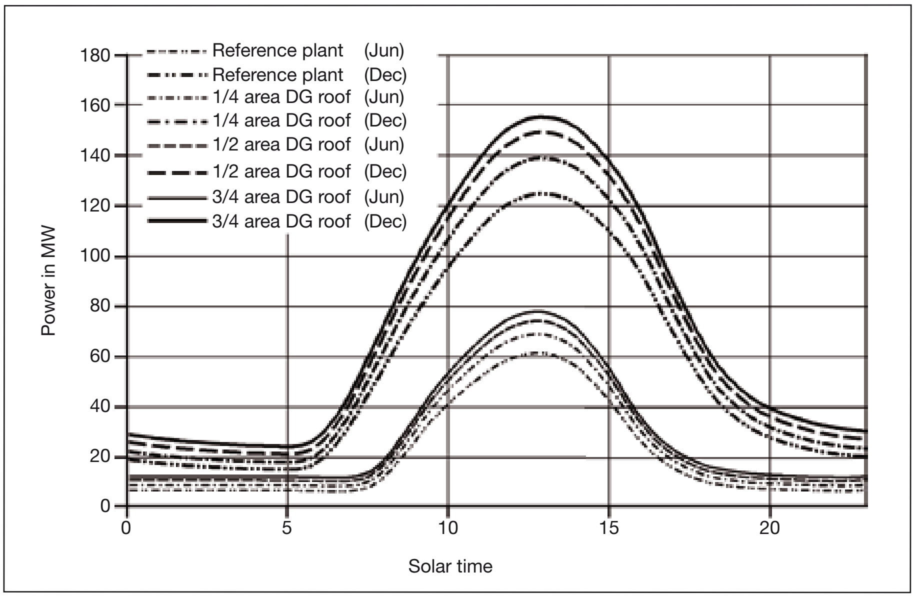

Figure 4. Effect of SCPP performance for a partially double glazed (DG) CA.

plant performance, namely in the order of 13 to 30%.

Methods of enhancing and controlling solar chimney power plant output have been investigated in detail by [20]. This study e.g. shows that double glazing of the collector roof improves plant performance, as illustrated in Figure 4. Here the reference plant refers to the standard plant used in Figure 3. Further simulation results also indicate that by employing a secondary collector roof with airflow-regulating mechanisms, it becomes possible to achieve significant dynamic control over the power output generated by the SCPP, namely to operate the plant either as base or as peak load facility as originally proposed by Kröger (see Figures 5 and 6). Here the power generation again refers to the standard plant in Figure 3. The incorporation of plastic covered water tanks [23] also proved a good mechanism for a static power output control, giving a much more uniform daily output profile compared to a plant without such tanks. It should be emphasized that all basic parameters for these simulations had been measured in large-scale physical experiments.

Special Aspects of Loads on Solar Chimneys

Wind Load and Wind Load Effects

Wind effects together with dead load dominate the feasibility of the tower, and to some extent also of the collector roof. Wind attacks the chimney first statically, considered as constant in time, which is caused by the mean wind speed. Secondly, a broad-banded dynamic loading originates from wind turbulence. Thirdly, vortice-shedding induces on both sides of the chimney a narrow-banded dynamic excitation (*v. Kármán* vortex street). All these loadings are well investigated in theory and in experiments for the lower parts of the atmospheric boundary layer (ABL).

Commonly, *Prandtl's* shear layer concept of fluid mechanics provides an adequate basis to describe the natural wind flow and to derive wind loads on structures up to heights of 300 m. This model subdivides the wind flow into mean and fluctuating components. The wind profile specifies the increase of the mean wind speed, so the mean wind load as function of the height z above ground. The standard deviation of the wind speed fluctuations describes the strength of turbulence, i.e. the mentioned broad-band dynamic load, approximately constant throughout the *Prandtl*-layer.

For solar chimneys, this model has to be reconsidered since these structures reach far beyond the atmospheric *Prandtl*-layer into the *Ekman*-layer. Here, *Coriolis*-forces have to be added to the usual friction and pressure gradient forces. The *Coriolis*-forces increase the mean wind speed, diverting the flow from the direction of the isobars according to the *Ekman*-spiral.

A 1500-m-tower e.g. even exceeds the height of the ABL thickness δ, where the ABL ends and the geostrophic wind flow prevails, dominated by pressure gradients and *Coriolis*-forces. Both are in equilibrium with the flow direction tangential to the isobars. At $z \geq \delta$, the shear becomes negligible, meaning that random turbulence and corresponding dynamic load components vanish. Here experimental meteorological data are scarce. However, theoretical considerations provide reliable models as developed by Harris and Deaves [12] for the mean and fluctuating load components. Basic parameters therein are the roughness length z0 and the thickness δ of the ABL.

The material properties of the fluid, especially its density $\rho = \rho(z)$ and viscosity, vary over tower height. At 1500 m above ground the mass density is 87 % of its value at ground level. The mean velocity pressure q_m diminishes accordingly:

$$\frac{q_m(z)}{q_m(10)} = \left(\frac{V_m(z)}{V_m(10)}\right)^2 \frac{\rho(z)}{\rho_0}, \qquad (1)$$

an effect which may advantageously reduce the total wind load on the tower.

The components of wind turbulence are described by the standard deviation (r.m.s.-values) of the velocity fluctuations: σ_u in the direction of the mean wind, σ_v in horizontal (lateral) direction, and σ_w vertically. Commonly in meteorology the r.m.s.-values are assumed constant in the *Prandtl* layer. Beyond approximately z = 200 m, the r.m.s. fluctuations decrease linearly with the distance to the

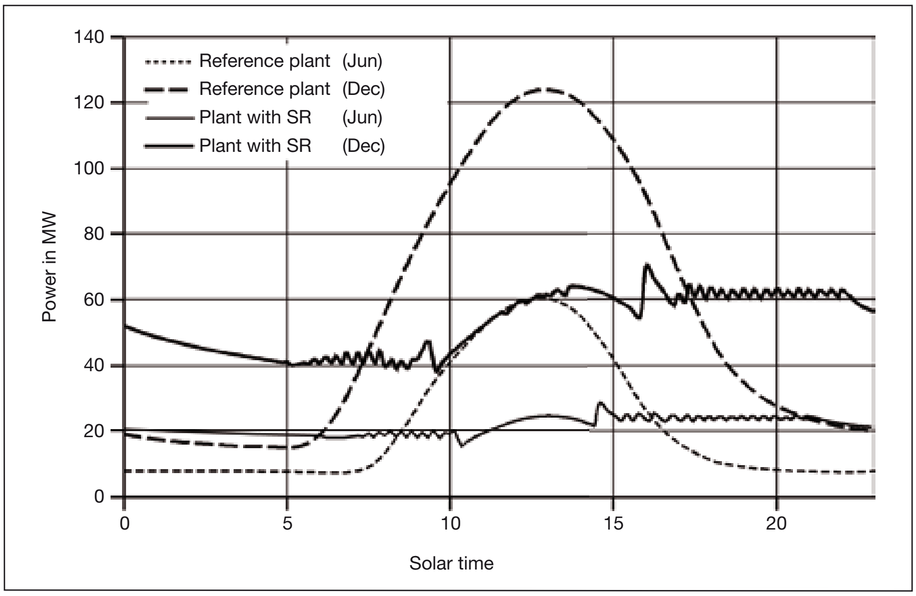

Figure 5. Daily SCPP performance with secondary roof (SR) as base load facility.

ground, and become zero at boundary layer height $z = \delta$. Such properties are included in the loading for description of the dynamic forces by means of the turbulence intensity function I_u.

This intensity I_u is the ratio of the r.m.s.-value of the velocity fluctuations to the mean velocity. It decreases with the height above ground. *Deaves* and *Harris* [12] have based their model on the following parameters: thickness of the ABL δ, roughness length of the terrain z_0, and shear velocity u^*. V. *Kármán's* constant is introduced with $\kappa = 0.4$. The variation of the r.m.s.-value is then given by:

$$\frac{\sigma_u(z)}{\sigma_{u10}} = \frac{(\mathbf{0.539} + \mathbf{0.09}\ln(\mathbf{z}/\mathbf{z_0}))^{(1-(z/\delta))^{16}}}{(\mathbf{0.539} + \mathbf{0.09}\ln(\mathbf{10}/\mathbf{z_0}))^{(1-(10/\delta))^{16}}} \frac{\mathbf{1}-(\mathbf{z}/\delta)}{\mathbf{1}-(\mathbf{10}/\delta)} \qquad (2)$$

The linear term $(1 - z/\delta)$ dominates for $z/\delta > 0.2$, such that the approximation

$$\frac{\sigma_u(z)}{\sigma_{u10}} = (\mathbf{1}-\mathbf{1.1}(\mathbf{z}/\delta)) \qquad (3)$$

holds for $z < 1500$ m.

According to our investigations, this theoretical model is an excellent basis of the wind load on solar chimneys. Regarding the broadband excitation by wind turbulence it is questioned whether resonance with the natural frequencies of the structure will become important. Both, beam-like bending modes and ovalling shell modes of vibration, may be excited. The variation of the spectrum of turbulence at high levels is under careful evaluation to provide a basis for future design calculations. Recent investigations indicate that natural frequencies of the tower can be designed sufficiently high to limit the level of resonance to wind turbulence. Turbulence also broadens the bandwidth of vortex excitation. Due to small atmospheric turbulence at high altitudes the excitation of the tower will be approximately mono-frequent with small vibrations. Resonance thus can be avoided by structural means to increase the natural bending frequencies as described in the next chapter.

The pressure distribution of the flow around the solar chimney is sensitive to its Reynolds number and to the surface roughness. The high trans-critical Reynolds numbers in the order of $Re \approx 4 \cdot 10^8$ have been approximately attained in full scale tests performed at hyperbolic cooling towers. The measurements provided static and dynamic wind loading data over the internal and external tower surface, such as

- mean pressure distributions in dependence of surface roughness;
- r.m.s.-pressure distributions and their correlation fields;
- pressure spectra and their coherence fields.

The data of these cooling tower experiences provide a reliable basis for estimation of static and dynamic wind pressures/forces on the solar tower for future model investigations in boundary wind tunnels (Figure 7).

Seismic Sensitivity

Occasionally the sensitivity of solar chimneys due to seismic excitation is questioned, probably due to their extreme height. The sensitivity of structures to earthquakes in general depends on their natural frequencies and the excited ground motions. A classical concept for quantification of the effect of earthquakes to a structure is to measure or to simulate the soil acceleration, and to compute time history responses on single degree of freedom oscillators. The maximal response functions of the oscillators plotted over their eigenfrequencies, so-called response spectra, are design bases also for solar chimneys.

Such design spectra generally exhibit their important contributions between 2 Hz (0.5 s) and 0.2 Hz (5 s), Figure 8. The lower eigenfrequencies of the fundamental oscillation of the beam-like behaviour of the solar chimney of approximately 0.1 Hz or T=10 s classify such towers as very soft cantilevers, optimally isolated against strong earthquake excitations. Some design-relevant internal stresses may arise from higher modes, but a dominant increase of the base bending must not be expected.

In detailed analyses the shell sections between the stiffening rings showed relevant seismic ovallising modes with eigenfrequencies from 0.30 ÷ 0.35 Hz leading to local bending. Serious aspects may also be found by systematic examination of the dynamic soil-structure interactions. The loading from the foundations and the subsoil due to both the impact of seismic waves and the reaction forces of the responding structure have to be considered. Subsequent and reflected, re-fractured and superimposed earthquake waves generate non-simultaneous (non-coherent) ground accelerations at the lower parts of the solar chimney. Investigations of such conditions show similarities with long-span bridges and long halls [13, 15]: Multiple asynchronous seismic excitations lead to an even lower overall seismic loading, whereas local effects in the structure and its foundations may then become relevant. This also holds for the vertical component of the seismic ground accelerations which may strongly affect the dimensioning of the substructure.

Solar Chimney Design and Construction

Loading and Response Characteristics

From the point of view of their load-response behaviour, solar chimneys are extremely enlarged, over-dimensioned cooling tower shells, demonstrating all those problems well known to cooling tower designers from more than 40 years of experience with such shell structures, namely:

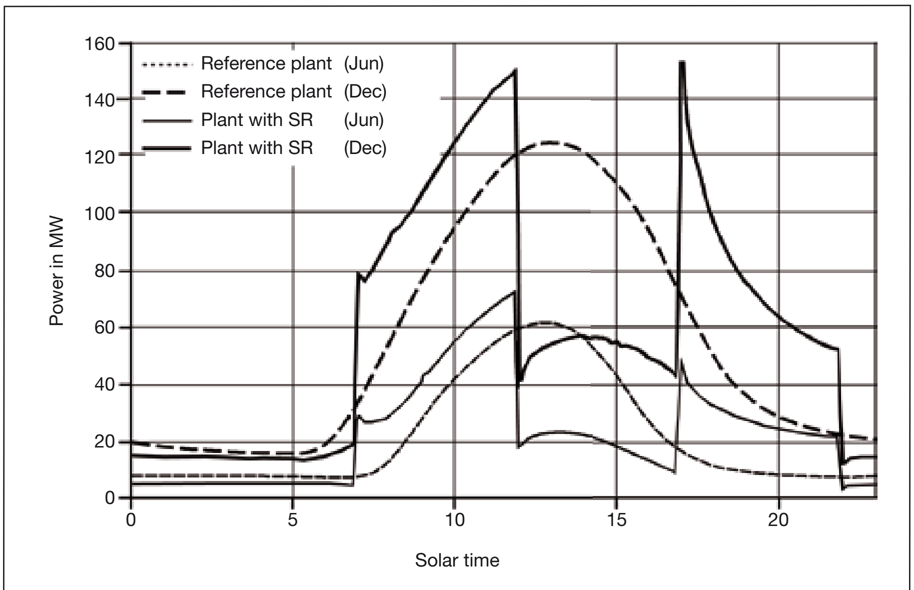

Figure 6. Daily SCPP performance with secondary roof (SR) as peak load facility.

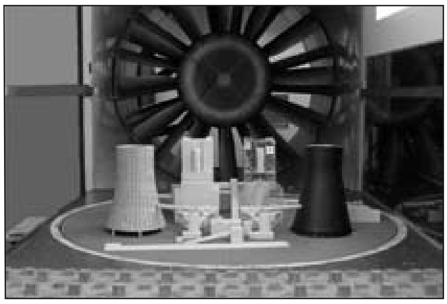

Figure 7. Boundary layer wind tunnel investigation of a thermal power station.

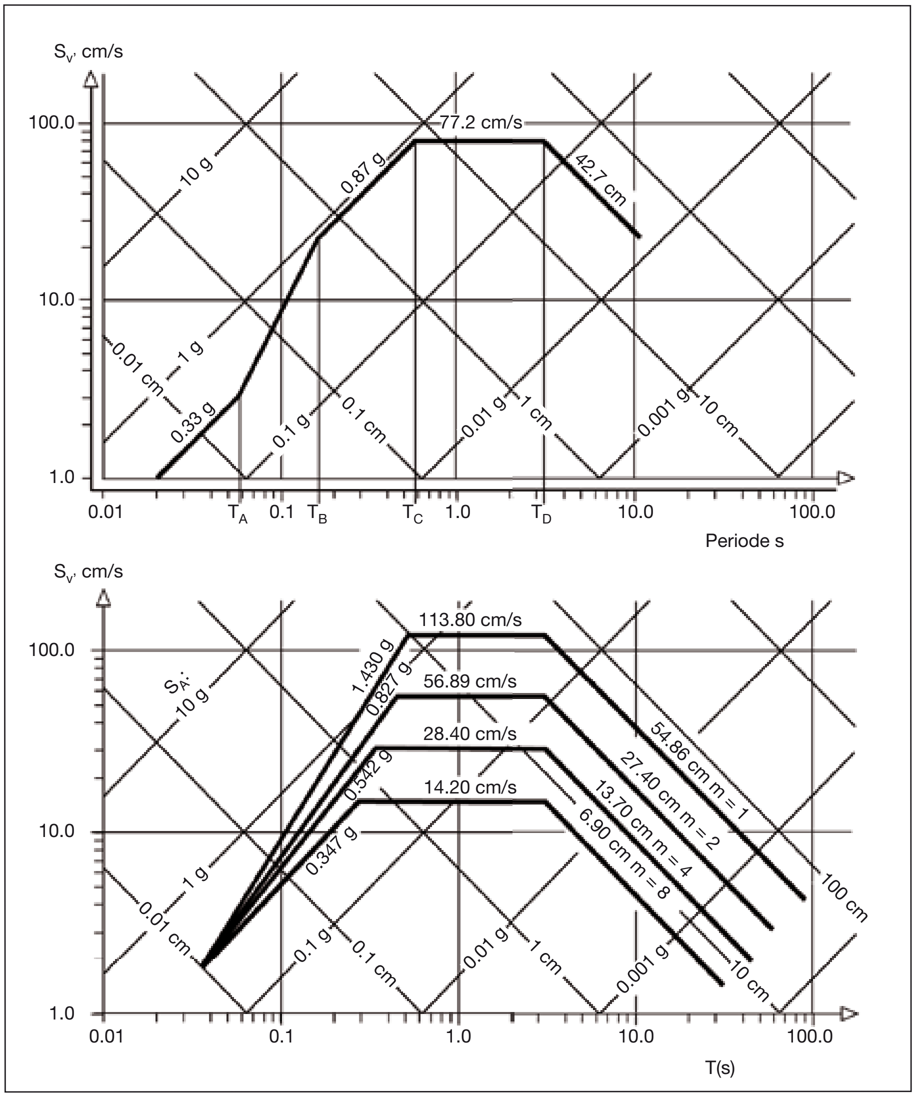

Figure 8. Elastic (top) and inelastic (bottom) design spectra due to Newmark-Hall.

- high compression stresses under dead-weight D and wind action W,
- tendency to vertical outside cracking under D, W and service temperature T,
- sensitivity to instabilities like shell buckling under D, W and wind suction S,
- forced wind vibrations including dynamic instabilities,
- strong sensitivity to soil-structure interaction phenomena,
- stress and thermal fatigue of concrete,
- durability problems on the long run of a SCPP's service live duration.

The structural design of a solar chimney is an optimisation process to compromise between several of these conflicting key points. However, the best known basis of any such design is the long-approved technical rule [26].

Figure 9 shows a series of such solar chimneys for SCPPs of different power capacity, pointing out its relationship to natural draft cooling towers. It emphasizes the enormous differences in size, but also the similarities of optimally designed SCs in structural shape, compared to the world largest cooling tower in Niederaussem [3]. Cooling towers are generally constructed without stiffening rings, mainly for reasons of durability, although such auxiliary means have been also applied there [14]. Solar chimneys up to 500 m of height can clearly be executed without any ring stiffeners, certainly with disadvantages to the stability and the maximum stresses. Chimneys of greater height require the application of strong ring stiffeners, with or without internal spokes, for stability, stress safety and for economical reasons.

1000 m Solar Chimney

As a more detailed example, Figure 10 shows a solar chimney of 1000 m of height for a 200 MW plant. The predominant parts of the shell will be constructed by use of high-performance concrete C 70/85, a concrete with compression strength comparable to (low quality) cast iron. In order to control possible cracking on the outer shell face, the concrete may be modified in the sense of a unilateral stress-strain-behaviour, such that its tension strength reduces to that one of a C 30/37. Experiences with such concrete have been gained at the Niederaussem cooling tower [3]. The thickness distribution over the height of the shell can also be seen from Figure 10.

In the upper two thirds the SC shell is formed due to fluid dynamics aspects as a conical frustum in upside-down position. It is stiffened by compression rings with a spacing of 100 m which may be additionally pre-stressed by spoke wheels fabricated of strings from carbon fibre resin. The spokes are directed in such a manner that their mechanical effects are maximum. In the lower third, the solar chimney shell applies the benefits of shape strengthening of shell structures: By use of a hyperboloidal meridional curve the shear stresses there are minimized. This leads to mainly meridional stresses in the narrow residuals of the tower shell between the turbine openings and so simplifies the tower foundation considerably [10].

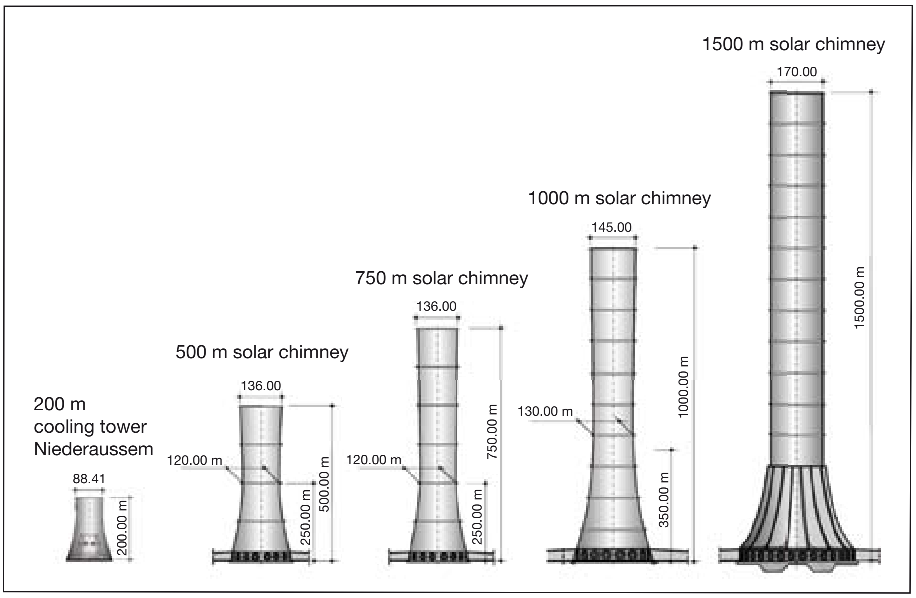

Figure 9. Variants of solar chimneys of different height.

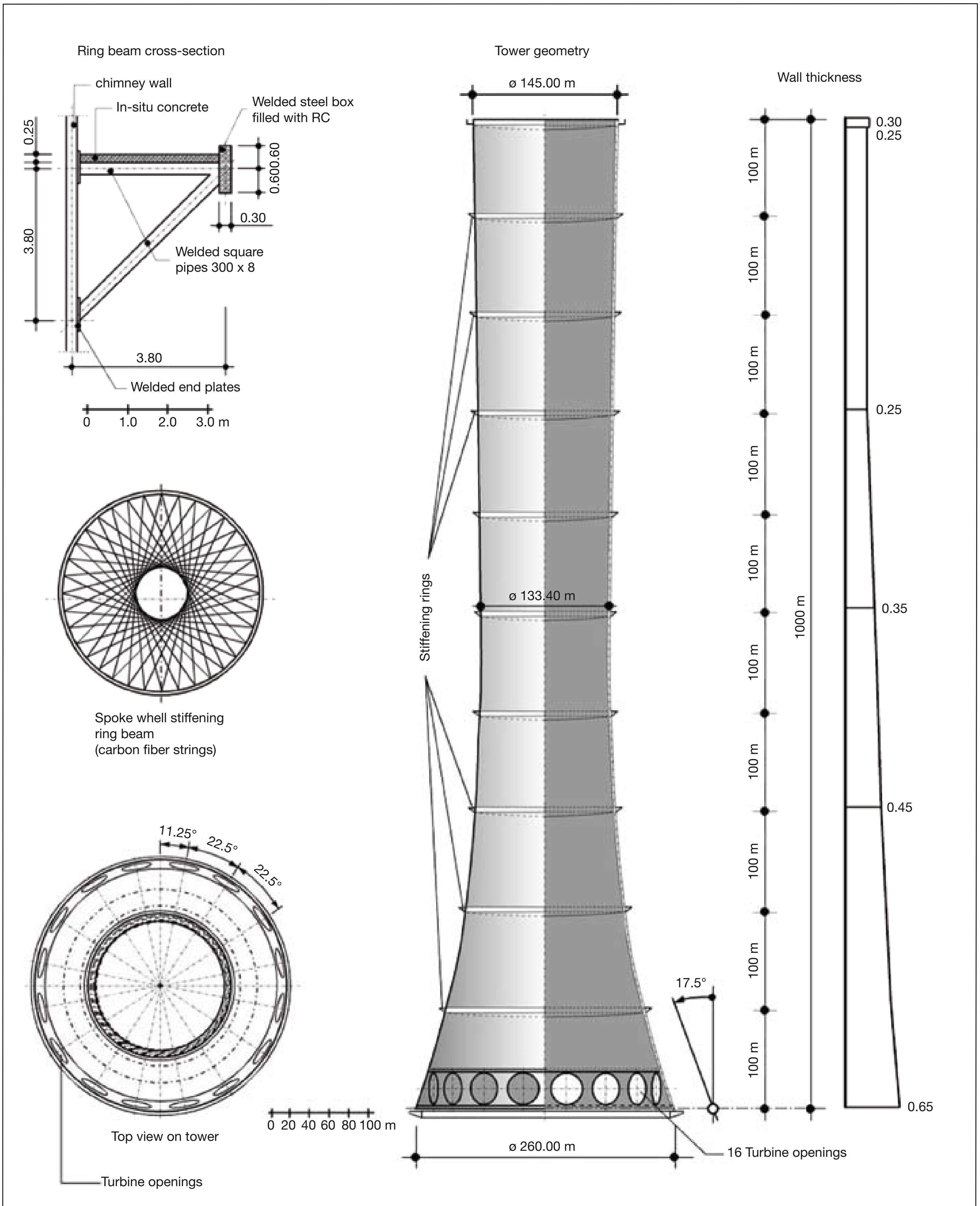

Figure 10. Details of a 1000 m solar chimney.

The turbine openings are stiffened by short cylindrical RC shell pieces, in which the turbo-generators rotate around their horizontal axes. Downstream of the turbine outlets, in the tower interior, membrane structures of Teflon®-coated glass-fibre fabric may provide for an optimised upwards flow of the heated air. These membranes are suspended on and pre-stressed against the chimney shell. Outside the turbines and not detailed in Figure 10, a ring of turbine houses is arranged for separated access for maintenance and repair. The turbine houses are connected to the glass roof of the CA, which is not treated here at all.

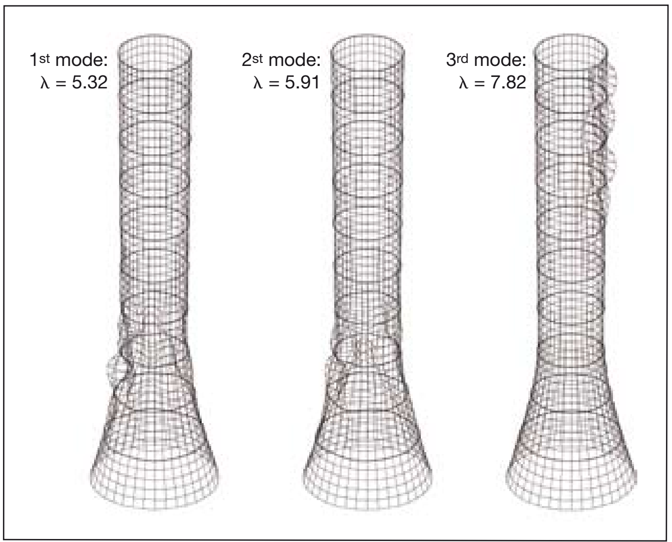

Figure 11. Instability modes and buckling safeties for D+W+S, for SC of Figure 10.

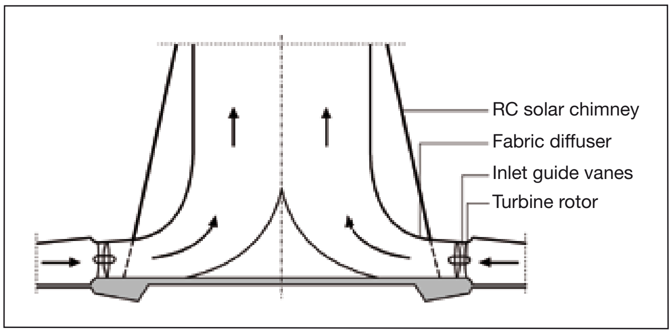

Figure 12. Scheme of a SCPP with multiple horizontal axis turbines.

The ring stiffeners in the course of the SC have to serve two mechanical duties. First, they have to force the cross sections from shell-like deformations to beam-like ones, and second, they have to increase the buckling stiffness of the chimney. The latter effect is demonstrated on Figure 11, where weak ring stiffeners lead to an unusual 3rd buckling mode in the upper shell parts. A slight stiffness increase by spokes removes these buckling modes, and increases the buckling safety of the entire structure.

Stability is only one of many aspects in the tower design. Generally speaking, the optimum shaping and ring-stiffening of the SC are those pre-requisites to allow an economical RC construction by use of classical climbing systems, and to guarantee suitable durability for the designed long service life of at least 80 years.

Characteristics of Solar Chimney Turbines

The specifications for solar chimney turbines are in many aspects similar to those ones for large wind turbines [1, 8]. They both convert large amounts of energy in the air flow to electrical energy and feed this into a grid. But there are also various important differences. The following characteristics are typical for solar chimney turbines in contrast to wind turbines.

In solar chimney power plants the turbines are ducted, and their maximum theoretically achievable total-to-total efficiency is therefore 100 %. The *Betz*-limit, which is applicable to wind turbines, is not applicable to ducted ones. Unfortunately, this has been implemented into various codes written for SCPPs, see e.g. [17].

The direction of the oncoming air flow is known and remains constant.

The turbines are protected from harsh weather conditions but have to cope with higher temperatures.

The large volumes of collector and chimney act as a buffer preventing large fluctuations in air flow speed, i.e. dynamic loads on the turbine blades and all the other rotating components are comparably low.

The visual impact of the turbine is small compared to that of the chimney and the collector.

The power output is mainly dependent on solar irradiation, which is much more predictable than wind, improving the power supply quality.

Furthermore, the turbine pressure drop in SCPPs is about 10 times bigger than in wind turbines [8].

Many of the recent advances in wind turbine technology will potentially be adapted to solar chimney technology, and will have an impact on the design and the cost of solar chimney turbo-generators. As an example, many modern wind turbines use a direct drive variable speed generator [4]. In most of the solar chimney literature it is assumed that a constant speed drive train would be used. A change to a variable speed drive train holds the potential for improved off-design performance.

Various turbine layouts and configurations have been proposed for solar chimney power conversion units (PCU). A single vertical axis turbine without inlet guide vanes was used in

Table 1. Optimum parameters for PCUs of various plant configurations from [6].

Configuration	Ref	Base	Peak	DG
Number of turbines	27	25	29	29
Turbine diameter, m	38.75	41.83	38.52	37.46
Blade length, m	11.62	12.55	11.56	11.24
Turbine speed, rpm	21.00	13.70	21.60	22.80
Maximum tip speed, m/s	42.61	30.01	43.57	44.72
Turbine load coefficient	0.24	0.30	0.26	0.25
Turbine flow coefficient	0.29	0.29	0.28	0.28
Degree of reaction	0.77	0.77	0.77	0.77
Turbine efficiency (tt)	0.89	0.90	0.90	0.89
Stator blades/turbine	32	32	32	32
Rotor blades/turbine	15	16	15	15
Rotor blade mass, ton	1.81	2.17	1.78	1.67
Generator length, m	1.49	1.40	1.53	1.49
Generator diameter, m	5.96	5.61	6.12	5.97
Generator mass, ton	70.93	61.33	75.47	71.39
Torque, MNm	2.31	1.93	2.50	2.33
Power/unit, MW	5.09	2.77	5.66	5.57
Initial capital cost, 10^6 €	96.1	88.8	108.2	102.2
Spec. PCU cost, €/kW	700	1284	660	633
Diffuser area ratio, -	1.30	1.20	1.22	1.29
Efficiency of PCU (tt)	0.78	0.80	0.79	0.79

Figure 13. One of several model turbines in the experimental power setup.

the pilot plant in Manzanares [25]. Such single vertical axis turbine layout using the chimney support structure as inlet guide vanes has also been proposed for a large-scale solar chimney [9]. Configurations with multiple vertical axis turbines have been proposed as well [24], and so have turbine layouts consisting of one pair of counter rotating rotors, either with or without inlet guide vanes [6]. It has recently been demonstrated, however, that a configuration with multiple horizontal axis turbines using a single rotor layout with inlet guide vanes (Figure 12) provides the lowest cost of electricity [7]. Table 1 shows optimum parameters for the PCU of various of the plants discussed in [7]. Therein "Ref" refers to the reference plant, "Peak" and "Base" to plants with secondary roofs and airflow-regulating mechanisms allowing for peak or base load operation. DG refers to a plant with the inner half of the collector double glazed, as mentioned already in this manuscript.

In comprehensive solar chimney performance models, as that one described in the paper at hand, it is commonly assumed that the conversion efficiency of the PCU is about 80 %, excluding exit losses [2, 21]. In the research leading to [7] it has been experimentally and theoretically demonstrated, for a wide range of plant geometries, that this is a reasonable global assumption (Figure 13).

Summary and Actuality of SCPPs for Germany

Solar upwind power generation is an interesting modern concept of renewable energy production in desert areas. It copies the daily natural solar uplift and downward air flows in the atmosphere, and gains electric energy out of it. Since it needs no fuel, it operates with the lowest known CO_2 emissions, originated only from the construction material and thus depending on the service life duration of the plant. The present publication has only touched the solar convector, but it should be mentioned that enormous progress has been made recently in raising the efficiency of it by use of specially coated glass sheets. Apart from the Manzanares prototype, SCPPs have not been erected up to now, also because of the enormous investment costs.

Although SCPPs work only with sufficient energy output in arid zones with an adequate solar irradiation, the mechanisms of the Kyoto Protocol, annex 2, to trade CO_2 emission certificates open an interesting gateway also to German energy suppliers. Especially in Central Europe with its limited energy resources, new innovative ideas of energy generation should be evaluated seriously by power technology experts, and should not be disregarded or even condemned in advance.

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