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Artikel: The principle

Autor: [s.n.]

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1. The principle

1.1 The basic concept

Solar chimneys convert solar radiation into electrical energy by combining in a novel way the principles of the greenhouse, the chimney and the wind-turbine generator (Figs 1+2) [1], [2]. In fact, even the idea of such a combination is not totally new [3], but only with the increasing costs of conventional energy on the one hand and the proven fact that huge chimneys are feasible [4], [5] on the other, has it appeared reasonable to pursue it.

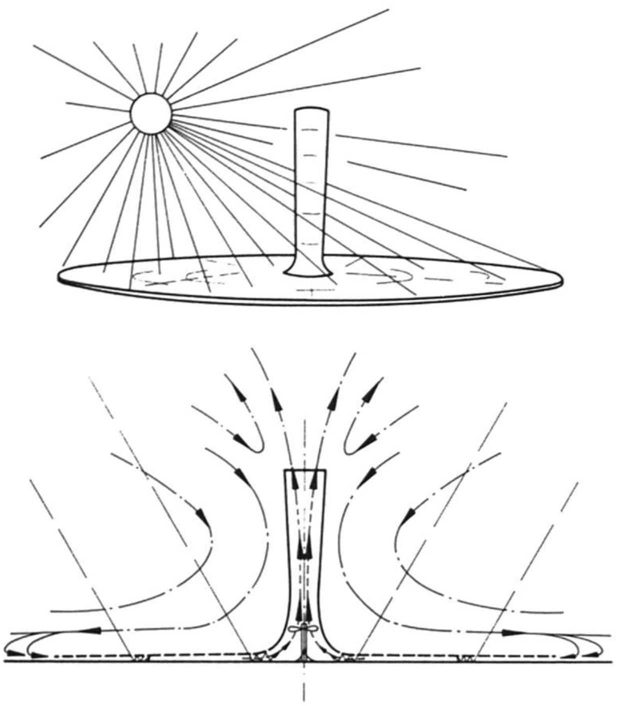

Fig. 2: The principle of solar chimneys

The "greenhouse" serves as the solar collector and covers a circular area. It consists of a horizontal canopy roof of translucent plastic or glass, open along its periphery and positioned at a low height above ground level; to increase absorption the ground is simply blackened. At the centre of the canopy roof is the chimney cylinder, around the base of which the roof is closely fitted. The opening of the base of the chimney is underneath the roof so that the air mass under the roof is sucked up through the chimney cylinder. Air thus enters the space underneath the roof at its periphery and flows towards the chimney, its temperature being raised by the action of the sun as it does so. This presupposes, of course, that the roof material is of a type which will create the necessary greenhouse effect, i.e., short-wave solar radiation must be able to pass through the roof and warm the blackened ground surface below, but the long-wave thermal radiation must not be allowed to escape (see Figs. 3 and 4); fortunately most translucent materials have this property to a certain extent. The warmed air creates an updraft in the chimney strong enough to turn a turbine placed there for generating electricity. The wind turbine is placed in the lower part of the chimney with its axis oriented vertically and is coupled directly to the generator.

The greater the difference in the temperature of the warm air mass underneath the roof and that of the outside air, and the higher the chimney, the higher is the velocity of the updraft in the chimney. The actual output of electricity depends upon the air flow quantity, and therefore also on the diameter of the chimney or turbine. The air temperature and air flow quantity involved are determined by the dimensions of the plant itself, i.e. the diameter and height of the circular roof, the optical and thermal characteristics of the roof material employed, and the type of soil in the area where the plant is located. Important soil characteristics are its capacity to absorb and store energy in the form of heat. These parameters and many others were subject to extensive investigations, calculations, and optimizing efforts aimed at determining the most cost-effective dimensions. This analysis process is briefly reviewed in the next section and thoroughly documented in [2].

Basically the solar chimneys possess a low degree of efficiency in comparison with other types of solar power plants [6], though this is offset by low collector costs. As the efficiency increases sharply with the absolute size of the plant, only plants with peak electricity generating capacities of 10 MW, or better still 100 to 500 MW, make sense (see Figs. 6+7). A peak generating capacity of 500 MW requires a chimney 1,000 m high and 300 m in diameter and a collector roof 10,000 m in diameter.

One great advantage of solar chimneys is their natural thermal storage capacity, which costs nothing. During the day, roughly one-third of the total radiance is reflected by the roof, one-third directly transferred into the working air and one-third absorbed by the soil. At night the soil releases its heat. Solar chimneys can therefore operate throughout the night and, depending upon their size and the soil characteristics at the site, still deliver 20% of their peak generating capacity on the following morning.

1.2 Physical and cost estimates

Energy balances, plant dimensions and power output

The first step in designing and optimizing a solar chimney is to determine the individual energy balances in the collector, which depend on its radius. Figure 4 shows the heat transmission for two different radii with single and double layer translucent films, respectively. Figure 5 shows the 24-hour course of ground temperatures for soil with good conductivity at various depths, derived from detailed model calculations. This curve reflects the above-mentioned storage effect.

The individual heat transmission values add up radially to the total enthalpy increase at the entrance to the chimney cylinder. The resulting increase in temperature ΔT generates the operating pressure and hence the updraft with the velocity v:

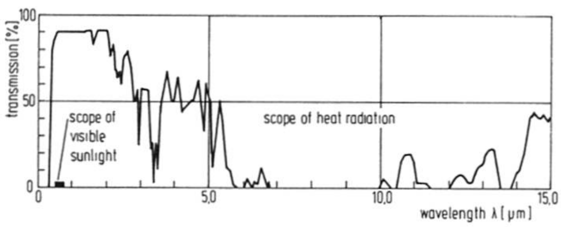

Fig. 3: The canopy roof: transmission spectrum of a polyester membrane, 125 μm thick

$$\Delta T = \eta_c \cdot \frac{J \cdot \pi \cdot R_c^2}{C_p \cdot \dot{m}} \quad (1)$$

$$v = \sqrt{2 \cdot \frac{\Delta p}{\rho_i}} = \sqrt{2g \cdot H_T \cdot \frac{\Delta T}{T_a}} \quad (2)$$

Both are connected through the air mass flow rate

$$\dot{m} = \rho_i \cdot v \cdot \pi \cdot R_T^2 \quad (3)$$

where:
- J: global radiance
- R_c: radius of collector
- H_T: height of chimney tube
- R_T: radius of chimney tube (const)
- η_c $(T, \dot{m})$: collector efficiency
- C_p: specific heat capacity of the air
- ρ_i: air density in the chimney cylinder
- T_a: ambient temperature at ground level
- Δp: generated pressure difference

Of course these equations involve major simplifications which forbid their use in actual design. Nevertheless they enable the basic interrelationship to be grasped immediately. The output given by $\dot{m}$ or v respectively ΔT increases when the collector area and the chimney height are increased.

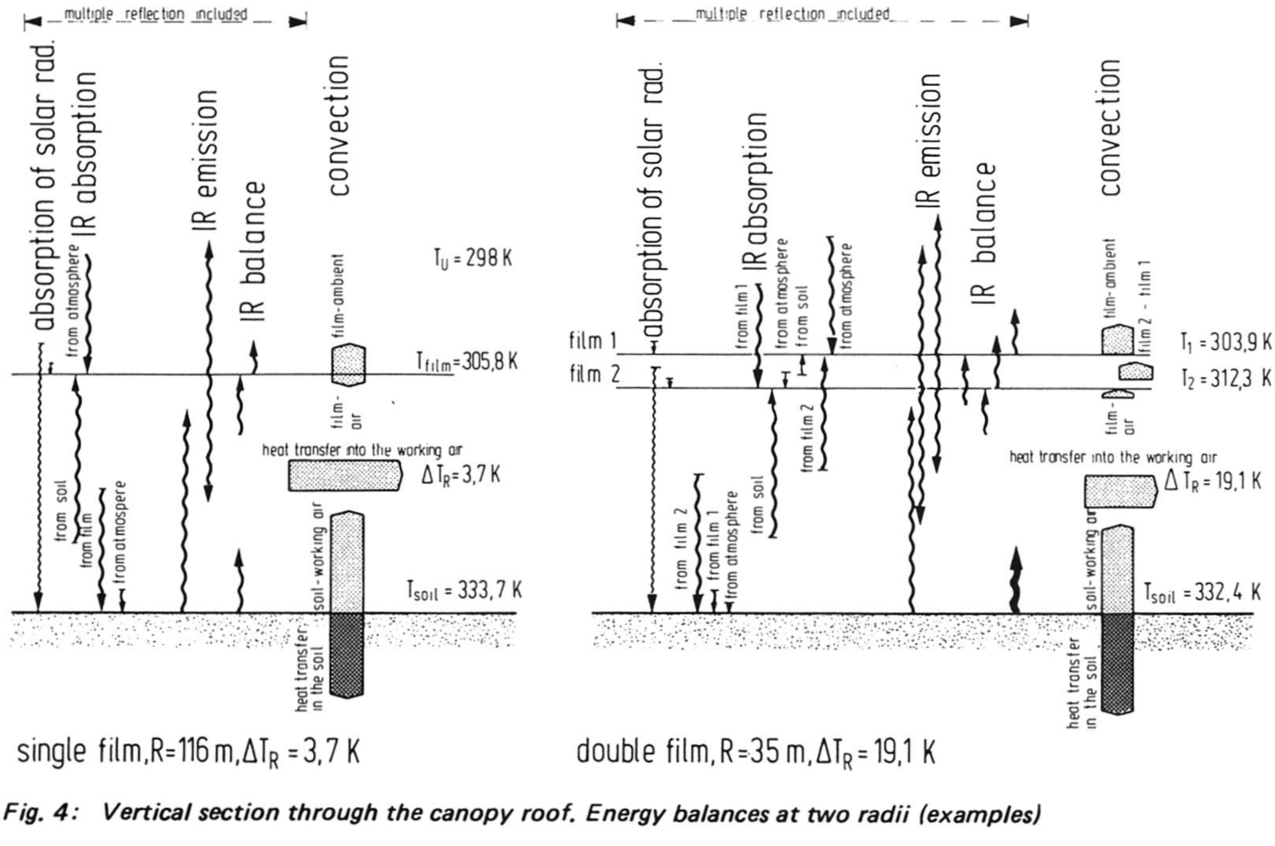

Fig. 4: Vertical section through the canopy roof. Energy balances at two radii (examples)

There is, however, an upper limit to ΔT, above which there is no point in increasing the size of the collector, since beyond it the losses due to radiation, convection and friction become excessive. Depending on the many parameters of the soil and the canopy, this limit may be reached around $\Delta T_1 = 15K$.

Taking at $\Delta T \approx \Delta T_1$ the proportion between the power output N and the upwind velocity approximately as $N \sim v^3$, we read from (2) that the tower height governs N according to $N \sim H_T{}^{3/2}$.

The electrical output of a wind turbine is

$$N_{el} = \eta_T \cdot \Delta p_T \cdot \dot{V} \quad (4)$$

where: η_T: efficiency of the turbine, the gearing and the generator

Δp_T: pressure drop at the turbine which can be taken for this type of turbine as $^2/_3$ Δp with Δp from equ. (2)

$\dot{V} = v \cdot A = v \cdot \pi \cdot R_T{}^2$: volumetric flow rate.

The combination of equ. (1), (2) and (3) in (4) with the inclusion of a further efficiency factor η_f for all frictional losses under the canopy roof and in the chimney, finally yields

$$N_{el} = \eta_c \cdot \eta_f \cdot \eta_T \cdot {}^2/_3 g \cdot H_T \cdot \pi \cdot R_c{}^2 \cdot J \cdot \frac{1}{c_p \cdot T_a} \quad (5)$$

The plot in Fig.6 is based on this equation, i.e. it shows how N_{el} depends on the main parameters H_T and R_c. Concerning η_c and η_f it is based on a detailed and far more complex simulation analysis which includes, among other parameters, the height of the roof and the radius R_T of the chimney tube. R_T is kept constant, i.e. the chimney is a cylindrical tube without diffusor. Since R_T is a major design factor, it is also included in Fig. 6.

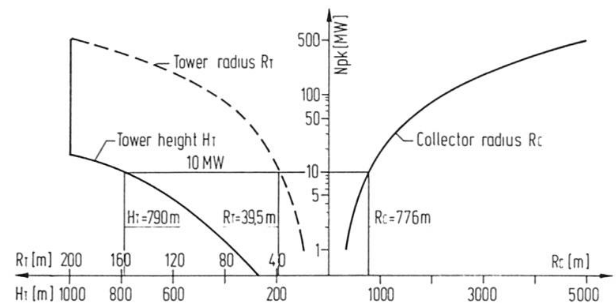

Fig. 6: Major design parameters of solar chimneys versus electrical output
N_{pk}: peak electrical output
H_T, R_T: height and radius of chimney tube
R_c: radius of collector roof

Cost estimates

Taking the above data and typical current prices as a basis, the specific installation costs were computed as shown in Fig. 7. It may be seen that with increasing plant dimensions the specific costs decrease; this is not because a cost reduction factor has been applied, but because the real physical efficiency increases.

From an economic point of view, however, it is the average power generating costs which count. They are expected to be around 0.25 DM/kWh (0.1 $/kWh). It would be beyond the scope of this paper to define and discuss all parameters such as local radiance, wind and soil conditions, maintenance, durability and repair, amortization period, interest and inflation rates etc., which had to be considered when computing them.

The recovery time for the primary energies required for the production of a solar chimney itself, a characteristic value in the comparison of solar energy installations, is expected to be around 5 years.

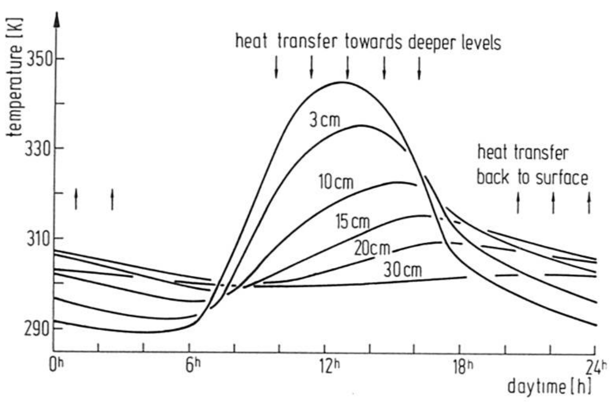

Fig. 5: Model calculation of soil temperature profiles (limestone) near the perimeter of the canopy

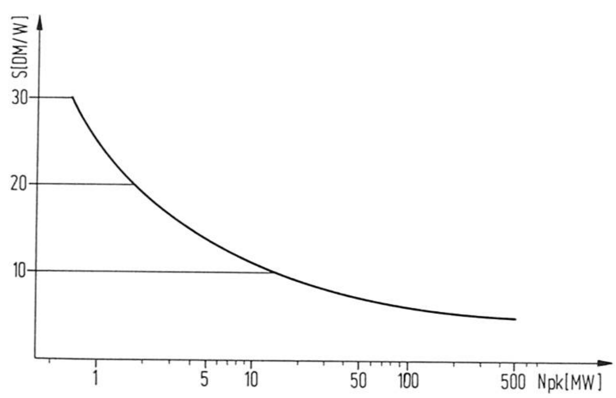

Fig. 7: Total specific installation costs of solar chimneys based on 1982 prices in West Germany