The Solar Chimney – an alternative configuration

Abstract

The solar chimney involves a tall cylindrical chimney at the centre of a large area solar collector with turbines at the base of the chimney to harness the kinetic energy of the air flow. The alternative configuration described in this paper involves horizontal axis turbines symmetrically sited around the circumference of the solar collector, each at the throat of a convergent nozzle in a sealed structure. The chimney proposed is an annulus (ring-shaped) involving two concentric walls built at around mid-radius of the collector. In this way a much larger area of cross-section of chimney is possible. If the chimney cross-sectional area is several times the total area of cross-section of the turbines, the venturi principle dictates that the velocity of air flow through the turbines is also several times its velocity through the chimney. Available kinetic energy for the turbines is increased by the square of this ratio.

A model configuration is outlined with collector diameter 1000 m and with 100 turbines of diameter 10 m sited symmetrically around the circumference. The chimney of height 300 m is an annulus of outer diameter 540 m and inner diameter 460 m. It is calculated that at insolation 750 wm^{-2} the air flow velocity through the turbines is 32.59 ms^{-1} providing available kinetic energy of 160.4 MW with an efficiency of 38.45%.

Introduction

The solar chimney advocated by Schlaich [1] has been the subject of several hundred research papers. It involves a tall cylindrical chimney at the centre of a large area solar collector with turbines at the base of the chimney to harness the kinetic energy of the air flow. It allows only very low efficiency.

The present proposal involves an annular chimney (ring-shaped) of moderate height and large cross-sectional area built as concentric walls at around mid-radius of the collector. A large number of turbines sited symmetrically around the outer circumference of the solar collector are driven by the incoming horizontal air flow. The total cross-sectional area suggested for the turbines is just a fraction of the cross-sectional area of the chimney. Air flow velocity through the turbines is thus several times air flow velocity through the chimney providing high efficiency.

The alternative configuration proposed is based on several considerations:

(1) Kalogirou [2] describes solar updraft towers (Figure 1) and includes the comments, “By placing a vertical wind turbine at the base of the tower or a number of horizontal turbines in a ring around the base of the tower, this updraft force can be used to produce electricity.” The relevant section is reproduced in Appendix 1.

Virtually all research papers on the solar chimney assume vertical air flow through the turbines sited at the base of the chimney. But here Kalogirou gives equivalent consideration to horizontally driven turbines and further suggests that they be placed “in a ring” around the base of the tower.

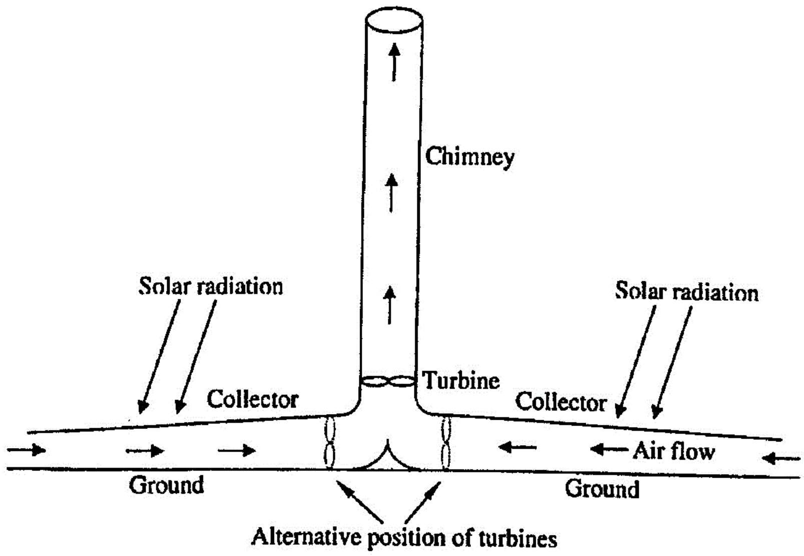

Figure 1

(2) Schlaich et al. [1, 3] gave careful consideration to horizontal axis wind turbines (Appendix 2). Indeed in their 2005 paper they say that, "Although one single vertical axis turbine arranged at the base of the tower might be seen as the straightforward solution, current designs and cost estimates are based on horizontal axis turbines arranged concentrically at the periphery of the tower, in order to realize redundancy, and also to be able to utilize turbines of existing sizes – particularly with regard to rotor diameter."

(3) Papageorgiou [4, 5] proposes an entirely new configuration described as "Enclosed Solar Chimney Power Plants". The solar collector is encircled by a peripheral wall with air turbines placed in proper openings on the peripheral wall. "The overall cross section area of the air turbines is several times smaller than the solar chimney cross section area. Thus the air speed entering into the air turbines is also several times higher than the speed of the up-drafting warm air inside the solar chimney."

This idea must be correct – it is the venturi principle. The velocity of air flow through the turbines is multiplied by the ratio of the area of cross-section of the chimney to the total area of cross-section of the turbines, compared to the velocity through the chimney. Available kinetic energy is multiplied by the square of this ratio.

(4) Divergent solar chimney

There have been several papers in recent years [6 – 9] that have claimed that divergent solar chimneys achieve higher efficiency than cylindrical solar chimneys. Hu and Leung [9] investigated solar chimneys of height 100-300 m and area ratio 0 to 32 (area ratio AR is the ratio of cross-sectional area at the top of the chimney to the base of the chimney). With an area ratio of 9-12 normalized power output is multiplied by a factor of 10-24. These are very substantial multiples that could change the economics of the solar chimney.

It is the present author's belief that available kinetic energy is multiplied by $(AR)^2$ in a divergent solar chimney [10]. There are problems however of flow separation at high AR and/or if the divergent angle is greater than 4°. Xu and Zhou [11] confirm that for chimney height 200 m output increases by a factor of 11.9 up to AR 8.7 and then decreases because of boundary layer separation, flow stall and backflow.

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The divergent solar chimney offers potentially massive efficiency enhancement because of the venturi effect but is severely limited by the problem of flow separation. **The Papageorgiou model potentially offers similar massive efficiency improvements again because of the venturi effect, but is not liable to flow separation.** Horizontal flow incoming air is accelerated by nozzles to high velocity as it flows through the turbines – but such flow is not liable to flow separation. **The Papageorgiou model offers the same efficiency enhancement as in the divergent solar chimney but without the problems of flow separation.** The alternative solar chimney configuration now proposed is shown in Figures 2 – 5.

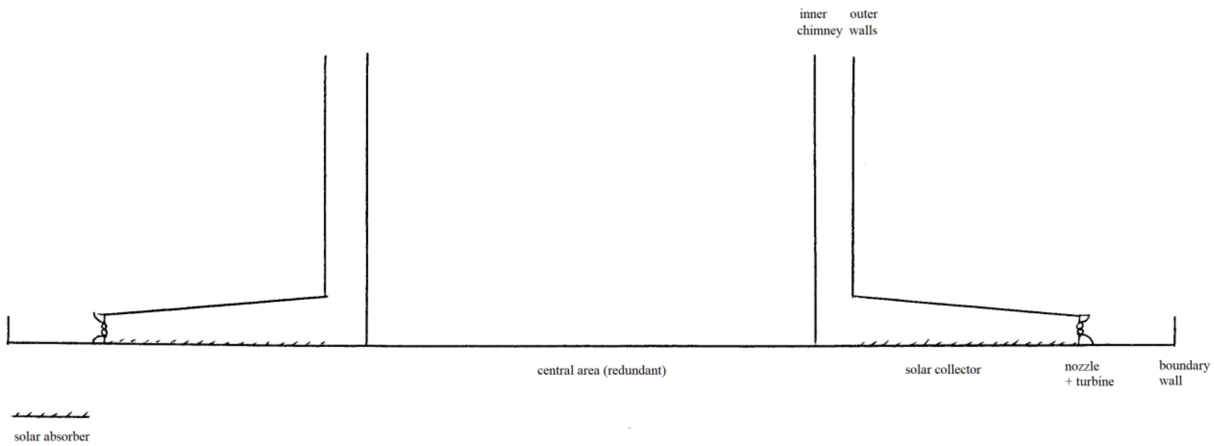

Figure 2 alternative configuration

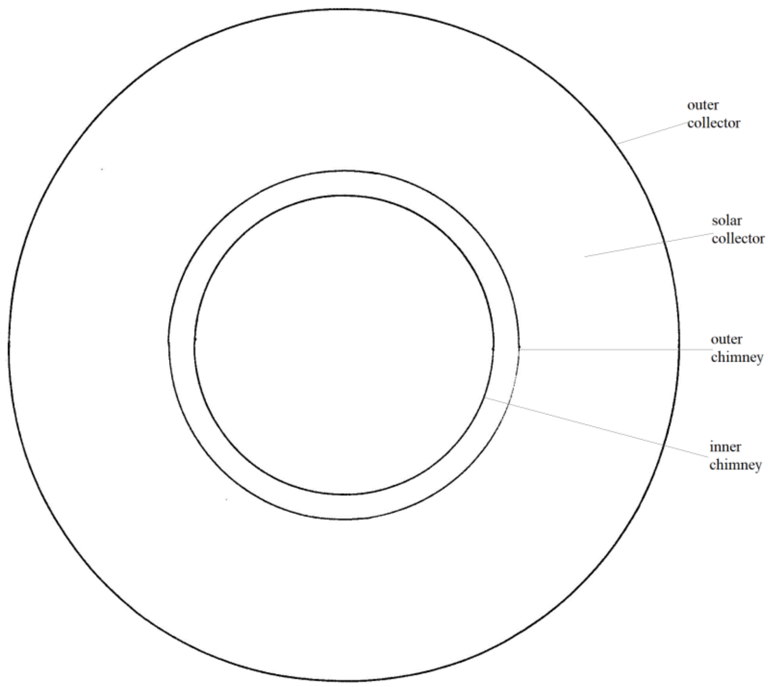

Figure 3 alternative configuration (from above)

An annular configuration is suggested for the chimney to allow a much larger chimney cross-sectional area. It is built of two concentric walls. The inner chimney wall is cylindrical and is a solid wall to ground level providing a very strong inner frame. The outer chimney wall must allow air flow from ground level to a considerable height above its base. It must stand on legs which carry the weight of the outer chimney. Steel cables from the inner to the outer chimney walls can reinforce the strength and stability of the outer wall.

The roof of the solar collector is made of glass and slopes gently upwards from its outer circumference to the outer chimney. The solar absorber is highly efficient and is placed above ground level and designed to allow rapid heat transfer to the air flow. Turbines are sited symmetrically around the outer collector each housed at the throat of a convergent nozzle (Figure 5). This allows smooth acceleration of incoming air flow to high velocity. The turbine converts this flow kinetic energy into electricity which is exported. Incoming air post turbine will be at below ambient temperature. It is suggested that the diameter of the mouth of the nozzle should be 3 times the diameter of the turbine. It then follows that the velocity of incoming air at the mouth of the nozzle is 1/9 the velocity of air flow through the turbine.

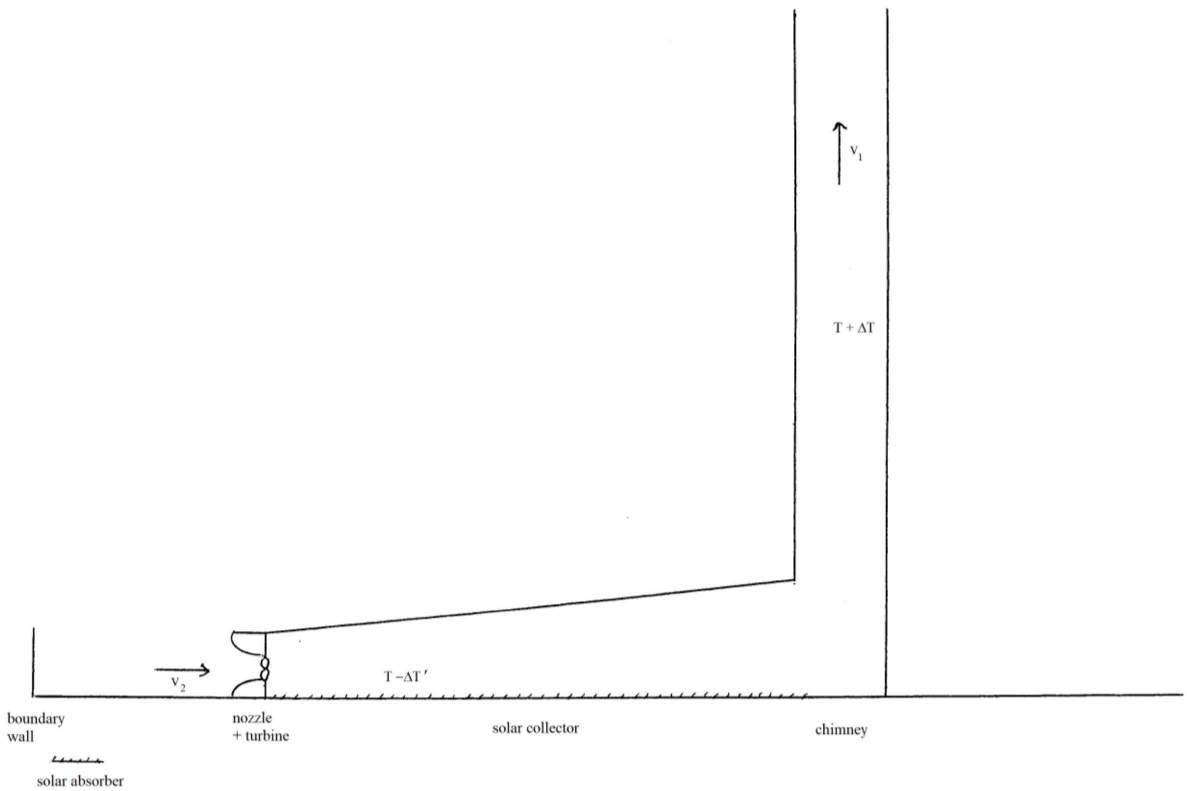

Figure 4 alternative configuration - radial section

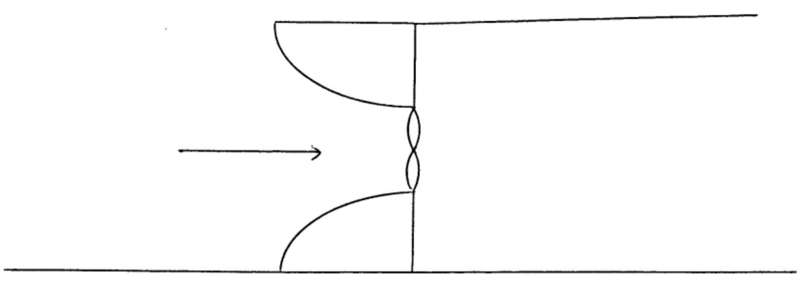

Figure 5 convergent nozzle and turbine

Overnight when there is no solar energy the configuration is inert. As the sun rises, the absorber takes up solar energy with high efficiency warming air in its neighbourhood which rises. A flow of air is established by natural convection where warm air flows from the collector to the chimney. The buoyancy of the warm air in the chimney draws replacement ambient air through the turbines generating electricity. Incoming air loses kinetic energy to the turbines with a consequent fall in temperature but this is replenished as it flows through the collector.

Output of the turbines is directly proportional to insolation. From zero at night, output rises continually from dawn to a daytime peak and diminishes to zero from evening to night. All changes should be smooth and continuous. Energy storage can be added using water tubes at ground level underneath the solar absorber [3]. This allows daytime solar energy to be stored for electricity generation in the evening and at night.

Theoretical Development

Consider that in Figures 2 - 5

h	height of chimney
A_1	area cross-section of chimney
A_2	total area cross-section of turbines
A_3	area solar absorber
v_1	velocity of air flow through chimney
v_2	velocity of air flow through turbines
T	ambient temperature
ΔT	excess temperature (above ambient) of exit air
$\Delta T'$	fall in temperature as air flows through turbines
g	gravitational constant
ρ	density of air at atmospheric pressure and temperature T
C_p	heat capacity of air at constant pressure and temperature T
I	insolation

The velocity of air through the chimney is given by the solar chimney equation [1, 3]

$$v_1^{\,2} = 2 \frac{\Delta T}{T} gh \qquad (1)$$

Assuming little change in density, constant mass flow requires that

$$A_1 v_1 = A_2 v_2 \qquad (2)$$

As incoming air is accelerated through the convergent nozzles the gain in flow kinetic energy is at the expense of internal energy and causes a fall in temperature $\Delta T'$

gain in kinetic energy = mass flow x heat capacity x fall in temperature

$$\tfrac{1}{2} \dot{m} v_2^{\,2} = \dot{m} C_p \Delta T'$$

where $\dot{m}$ is the mass flow

$$v_2^{\,2} = 2 C_p \Delta T' \qquad (3)$$

As incoming air flows through the solar collector, solar energy taken up by the absorber raises the temperature of the air flow from $\Delta T'$ below ambient to ΔT above ambient.

total solar energy absorbed	=	mass flow x heat capacity x temperature rise
$I\,A_3$	=	$\rho\,A_1\,v_1\,C_p\,(\Delta T + \Delta T')$ (4)

If we consider equations (1) – (4) they contain 8 variables $h\ A_1\ A_2\ A_3\ v_1\ v_2\ \Delta T\ \Delta T'$ and 5 constants $T\ g\ \rho\ C_p\ I$. If 4 of the variables are fixed the algebra is soluble. Thus any number of possible dimensions can be investigated.

Model Configuration

Consider that in Figures 2 – 5

- the outer solar collector is of diameter 1000 m, circumference 3140 m.
- there are 100 turbines each of diameter 10 m arranged symmetrically around the circumference, one turbine every 31.4 m.
- the chimney is of height 300 m, inner wall diameter 460 m, outer wall diameter 540 m, distance between walls 40 m.
- the solar collector forms the outer annulus from diameter 540 to 1000 m with a roof height of 30 m at the outer circumference rising to 50 m as air enters the chimney.

$$A_1 = \pi\,(270)^2 - \pi\,(230)^2$$
$$= 20{,}000\,\pi$$
$$= 62{,}800\ m^2$$
$$A_2 = 100 \times 3.14 \times (5)^2$$
$$= 7{,}850\ m^2$$
$$A_3 = \pi\,(500)^2 - \pi\,(270)^2$$
$$= 177{,}100\,\pi$$
$$= 556{,}094\ m^2$$

Thus in equations (1) to (4) consider that

h	=	300	m	T	=	300	^oK
A_1	=	62,800	m^2	g	=	9.81	ms^{-2}
A_2	=	7,850	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	556,094	m^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
				I	=	750	$w\ m^{-2}$

From equation (1)

$$v_1^{\,2} = \frac{2\ \Delta T}{300} \times 9.81 \times 300$$

$$v_1^{\,2} = 19.62\ \Delta T \qquad (1)$$

From equation (2)

$$62{,}800\ v_1 = 7{,}850\ v_2$$

$$v_2 = 8\ v_1 \qquad (2)$$

From equation (3)

$$v_2^{\,2} = 2 \times 1005\ \Delta T'$$

$$v_2^{\,2} = 2010\ \Delta T' \qquad (3)$$

From equation (4)

$$750 \times 556{,}094 = 1.18 \times 62{,}800 \times 1005\ v_1\ (\Delta T + \Delta T')$$

$$v_1\ (\Delta T + \Delta T') = 5.600$$

From (1) (2) and (3) above

$$v_1 \left(\frac{v_1^{\,2}}{19.62} + \frac{64}{2010}\ v_1^{\,2} \right) = 5.600$$

$$v_1^{\,3}\ (2010 + 1256) = 5.600 \times 19.62 \times 2010$$

$$v_1^{\,3} = 67.63$$

$$v_1 = 4.074\ \mathrm{ms}^{-1}$$

$$v_2 = 32.59\ \mathrm{ms}^{-1}$$

$$\Delta T = 0.8460$$

$$\Delta T' = 0.5285$$

Thus calculation gives ΔT and $\Delta T'$ at very modest values each below 1°C and the velocity of air flow through the turbines of 32.59 ms^{-1} at insolation 750 wm^{-2}. These are eminently reasonable values that could be harnessed by conventional wind turbines.

$$\text{Total insolation} = I\ A_3$$

$$= 750 \times 556{,}094$$

$$= 417.1\ \mathrm{MW}$$

$$\text{Available kinetic energy} = \tfrac{1}{2}\ \rho\ A_2\ v_2^{\,3}$$

$$= 0.59\ (7850)\ (32.59)^{3}$$

$$= \quad 160.4 \text{ MW}$$

Thus the maximum output is 160.4 MW at insolation 750 wm^{-2} representing an efficiency of 38.45%. The major inefficiency is heat loss in exit air but this is unavoidable as it is the buoyancy of warm air in the chimney that creates the air flow.

$$\text{Heat loss in exit air} \quad = \quad \text{mass flow x heat capacity x excess temperature}$$

$$= \quad \rho \, A_1 \, v_1 \, C_p \, \Delta T$$

$$= \quad 1.18 \times 62{,}800 \times 4.074 \times 1005 \times 0.8460$$

$$= \quad 256.7 \text{ MW}$$

Many variations are possible on the above model configuration eg the distance between the chimney walls could be reduced lowering A_1 and v_2 but also reducing output and efficiency. Conversely the distance between the chimney walls could be increased, increasing A_1 v_2 output and efficiency.

Further Comments

- No allowance has been made for energy losses through the glass of the solar collector or due to inefficiency of the turbines. The temperature of air in the collector is less than 1°C above ambient minimizing energy losses. Any energy losses in the turbine will be manifested as heat, giving a lower $\Delta T'$ and higher ΔT contributing to the buoyancy of air flow through the chimney. They are not lost to the system and are effectively recycled.

- Guo et al. [12] have drawn attention to the importance of the chimney slenderness ratio (SR) which is the ratio of the chimney height to its diameter, in ensuring smooth flow and suggest an optimum SR within 6-8. This has been taken into account in devising dimensions for the model proposed which has SR 6.25 to 7.5.

- The turbines are sited on the outer perimeter of the solar collector. They will thus be easily accessible for maintenance and renewal. This is also the case for electrical equipment and connection. The chimney, solar absorber and collector are less accessible but have no moving parts and will need less maintenance.

- The central area of the model configuration is redundant; it is a circular area of land of diameter 460 m. It could simply be disregarded or constructive uses developed but access would have to be by tunnel or by losing a small sector of the circular configuration.

- Dust problems can be minimized by construction of a boundary wall of 30 m height at a distance of 100 m from the perimeter of the collector. Incoming air is then drawn from a height of over 30 m around the collector.

Conclusion

An alternative configuration for the solar chimney is outlined with turbines sited around the circumference of the solar collector and with an annular chimney. Calculation shows that with collector diameter 1000 m, chimney height 300 m, chimney diameter 460/540 m and insolation 750 wm^{-2} air flow velocity through the turbines is 32.59 ms^{-1} generating 160.4 MW output with an efficiency of 38.45%.

The author asks experts on the solar chimney to consider the proposal and to assess its prospects for development.

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Appendix 1 [2]

10.6 Solar updraft towers

The solar updraft tower is a renewable-energy power plant for generating electricity from solar power. The principle of operation of a solar chimney or updraft power plant is that because of its lower density hot air rises and creates a draft. The system consists of a chimney, a solar energy collector and wind turbines. In the collector, which is a large area of covered land, air is heated by solar radiation under a transparent (glass) or translucent (plastic) roof. This heat is forced upward through the chimney thereby creating a wind force as the joint between the roof and the tower base is airtight. Suction from the tower then draws in more hot air from the collector, and cold air comes in from the outer perimeter.

By placing wind turbines at the base of the tower the wind force can be used to produce electricity. One advantage of the system is that the collector itself functions as a greenhouse and could be used for growing various crops. The solar updraft power technology has relatively low conversion efficiency and relatively high investment costs per MWh of electricity produced, but the operating costs are very low. The technology is particularly suitable in remote areas where low-value land can be used for the heat collection.

A schematic diagram of a solar updraft tower is shown in Figure 10.14. Solar updraft towers make use of differences in temperatures of air near the ground and at the top of the tower or chimney. Through the chimney effect, i.e., forcing the air through a relatively small opening, the wind force becomes very strong. By placing a vertical wind turbine at the base of the tower or a number of horizontal turbines in a ring around the base of the tower, this updraft force can be used to produce electricity. As the only source of energy is solar energy, the solar updraft tower functions as a solar thermal power plant. Over the day the ground gets heated and over the night it gives its warmth to the ascending collector air. Continuous 24 h operation can be best achieved by placing water-filled tubes or bags under the roof. The water heats up during daytime and releases its heat at night. The tubes are filled with water only once (no further refilling is required) to increase the effect. Black colored bodies

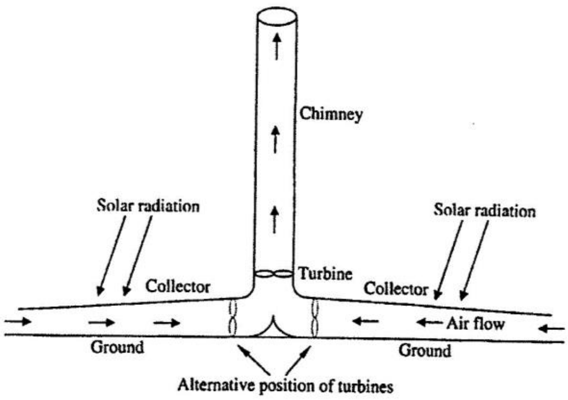


FIGURE 10.14

Schematic diagram of a solar updraft tower.

have the ability to absorb short wavelength radiation during the day to heat the water and emit long wavelength heat at night to warm the air.

Hot air for the solar tower is produced by the greenhouse effect in a simple air collector consisting of a nearly horizontal glass or plastic glazing installed several meters above the ground. The height of the glazing increases near the tower base, which has a smooth entrance so that the air is diverted to vertical movement with minimum friction loss. Therefore, the ground under the transparent roof is heated and transfers its heat to the air flowing radially inside the tower.

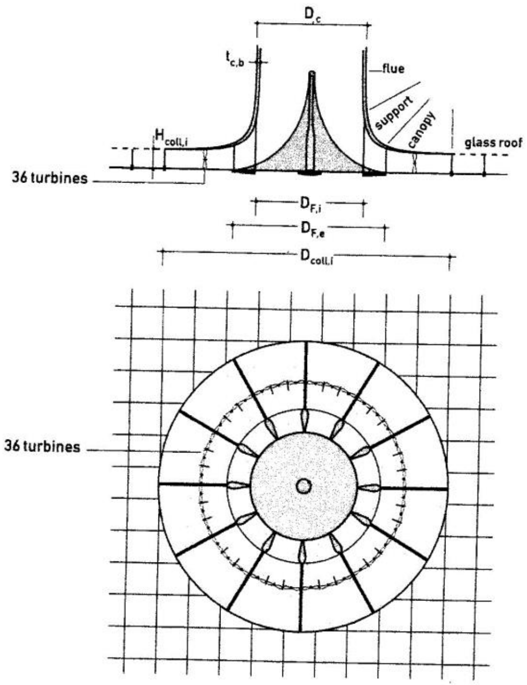
The requirement of a relatively large area implies that the technology is particularly suitable in those countries which have large areas of desert-type land.

A good review on the developments and advancement of solar chimney power plants is presented by Bernandes (2010).

The energy efficiency of the solar updraft tower is low. Therefore, a relatively large area is required for collecting the heated air in combination with a tall chimney. It is estimated that for a 200 MW capacity plant, the solar collector should have an area of 38 km^2 and the chimney height is 1000 m (Schlaich et al., 2005). The conversion efficiency of such a plant would be about 0.5% (or 1 kWh/m^2). The capital costs for such a plant would be relatively high as it requires a specialized expertise mainly for the tower construction, but the running costs would be very low and concern mainly maintenance of the wind turbines. However, when plastic is chosen as the cover for the solar collector, then this will require replacement every few years. Producing electricity with such a 200 MW solar tower would cost €0.07 per kWh whereas it would cost €0.21 per kWh for a smaller 5 MW plant due to economies of scale (Schlaich et al., 2005).

Appendix 2

[1] page 15



[1] page 35

For mechanical design, it was possible to use a great deal of experience with wind power stations, cooling tower ventilation technology and the Manzanares solar chimney's years of operation. Although **vertical axis turbines in groups of six** arranged at the base of the tower are seen as the correct solution, **fig. 8b**, the cost estimate was based on horizontal axis turbines arranged concentrically at the periphery of the tower, in order to be able to utilize turbines of existing sizes – particularly with regard to rotor diameter. **Fig. 8c.** Aerodynamic design for entrance area and turbines was achieved by means of wind tunnel airflow experiments.

[1] page 21

8c chimney base as in 8b, but with 36 horizontal axis wind turbines at the perimeter of the chimney support.

Turbines are always placed at the base of the chimney. Vertical axis turbines are particularly robust and quiet in operation. The choice is between one turbine whose blades cover the whole cross-section of the chimney or six smaller turbines distributed around the circumference of the chimney wall; here the blade length of each turbine will be a sixth of the chimney diameter. **Fig. 8b.** The diversion channels at the base of the chimney are designed for one or six turbines as appropriate. But it is also possible to arrange a large number of small turbines with horizontal axes (as used in cooling tower fans) at the periphery of the transitional area between canopy and chimney. **Fig. 8c.** The decision is made according to the size of the plant and available technology. Generator and transmission are conventional, as used in current wind turbine applications.

[3] **Technology**

Structural design of large plants showed that a glass collector of the Manzanares design can be used for large plants without major modifications. This design represents a proven, robust and reasonably priced solution. The Manzanares experience also provided cost calculation data for the collector.

Towers 1,000 m high are a challenge, but they can be built today. The CN tower in Toronto, Canada, is almost 600 m high and serious plans are being made for 2,000 meter skyscrapers in earthquake-ridden Japan. What is needed for a solar tower is a simple, large diameter hollow cylinder, not particularly slender, and subject to very few demands in comparison with inhabited buildings.

There are different ways of building this kind of tower: Free-standing in reinforced concrete, guyed tubes with skin made of corrugated metal sheet, or also cable-net designs with cladding or membranes. The respective structural approaches are well known and have been used in cooling towers. No special development is needed.

With the support of international contractors especially experienced in building cooling towers and towers, manufacturing and erection procedures were developed for various tower types in concrete and steel and their costs were compared. The type selected is dependent on the site. If sufficient concrete aggregate materials are available in the area and anticipated seismic acceleration is less than about one third of the earth's gravitational acceleration, then reinforced concrete tubes are the most suitable. Both conditions are fulfilled world-wide in most arid areas suitable for solar towers. Detailed statical/structural research showed that it is appropriate to stiffen the tower at several levels with cables arranged like spoked wheels within the tower, so that thinner walls can be used. This is maybe the only really new feature of solar towers compared to existing structures.

For mechanical design, it was possible to use a great deal of experience from hydro and wind power stations, cooling tower ventilation technology and the Manzanares solar tower's years of operation. Although one single vertical axis turbine arranged at the base of the tower might be seen as the straightforward solution, current designs and cost estimates are based on horizontal axis turbines arranged concentrically at the periphery of the tower, in order to realize redundancy, and also to be able to utilize turbines of existing sizes - particularly with regard to rotor diameter. Aerodynamic design for entrance area and turbines was achieved by means of wind tunnel airflow experiments and computer fluid dynamics.