The Solar Chimney – an alternative configuration (2)

A Model for the Design of Large, Efficient Solar Power Stations

Abstract

A new configuration is proposed for the solar chimney involving three concentric circles. The outer two circles form an annular chimney (ring-shaped) which offers a very large area of cross-section for the air flow and much larger buoyancy forces. The inner circle provides the entrance to the solar collector. Turbines are sited symmetrically around this inner circumference generating electricity from incoming air.

A model configuration is proposed of chimney diameters 1000 and 960 m and height 200 m. The solar collector has an inner diameter of 600 m with 60 turbines each of diameter 10 m around its circumference. It is calculated that insolation 750 wm^{-2} generates air flow velocity 39.71 ms^{-1} through the turbines providing available kinetic energy of 174.0 MW with an efficiency of 52.64%. Larger models are also described with output of up to and over 1000 MW and efficiency about 50%.

Introduction

The solar chimney developed by Schlaich et al. [1] relies on natural convection as its driving force but even with a very tall chimney (1000 m) efficiency is low. The divergent solar chimney multiplies efficiency by a considerable factor but is awkward structurally and is limited by problems of flow separation. This is discussed in an earlier paper by the present author [2] who proposes an alternative configuration involving the use of an annular chimney (ring-shaped). This provides a much larger area of air flow to generate buoyancy. The author also adopts the suggestion by Papageorgiou [3] that the turbines be sited on the outer circumference of the solar collector generating electricity from incoming air flow. An expert on the solar chimney H.-J. Niemann [4] suggests that reversing the roles of the concentric rings in the alternative configuration would provide a naturally higher velocity. This latter modification is incorporated into the new proposal.

The Solar Chimney – an alternative configuration (2)

The new configuration proposed is shown in Figures 1 – 3. The annular solar chimney (ring-shaped) has a diameter of 1000 m with walls of height 200 m at a distance apart of 20 m,

The outer chimney wall has no break in continuity and is of solid, strong construction to ground level. It provides a robust outer framework and protection against wind and weather.

The inner chimney wall must allow air flow from ground level to about one quarter of its height. It is of light construction with its weight borne on legs around the circumference and its stability maintained by a network of cables to the outer wall.

The inner circle of the solar collector is of low height and solid construction with openings only for the turbines which are sited symmetrically around the circumference. Incoming air is accelerated to high velocity by convergent nozzles built into the structure. It is suggested that the diameter of the mouth of the nozzle should be 3 times the diameter of the turbine.

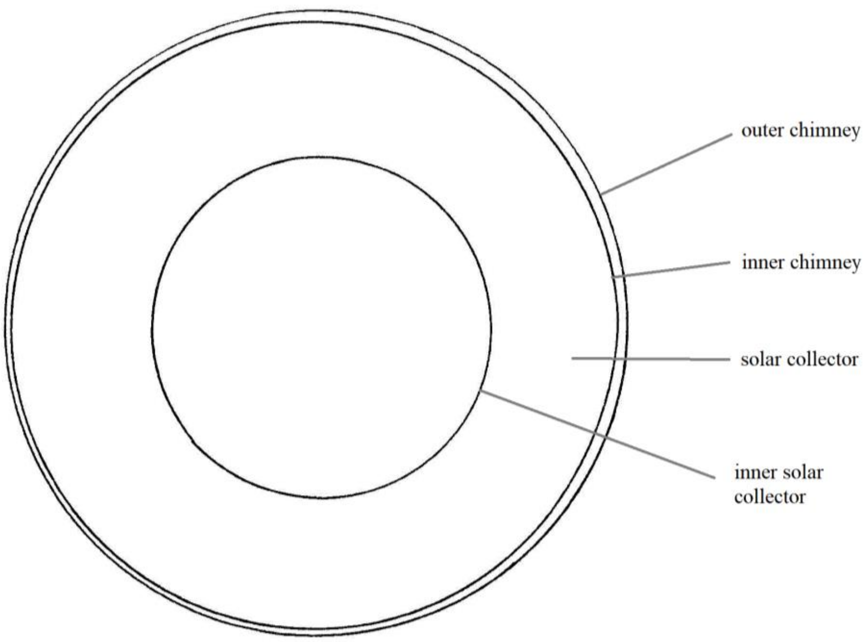

Figure 1 (aerial view)

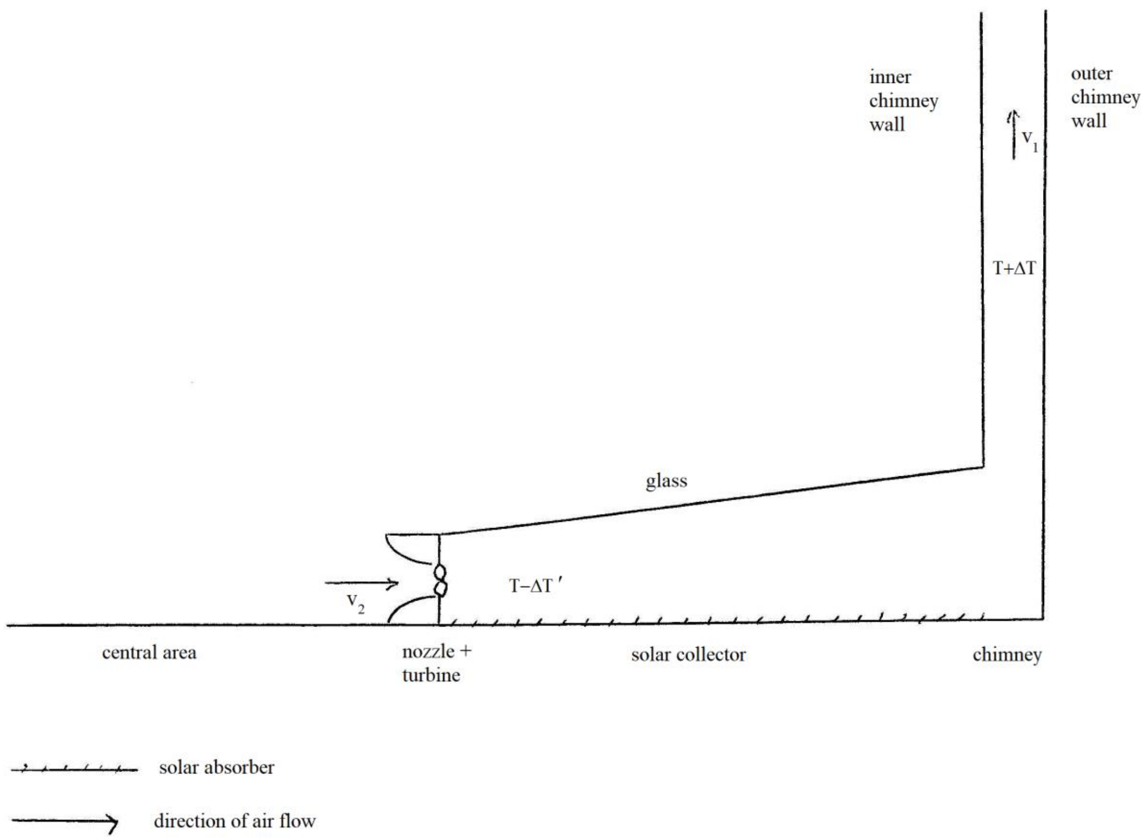

Figure 2 (radial section)

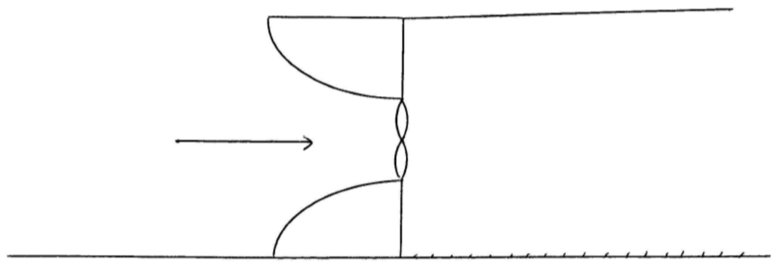

Figure 3 convergent nozzle and turbine

The central area is largely redundant but allows access of ambient air from above into the nozzles, turbines and solar collector. It also provides excellent access to the turbines, electrical equipment and to the solar collector for maintenance and repair.

The solar collector takes up the overwhelming majority of the total area. It has a roof of glass or transparent plastic, gently sloping upwards towards the chimney. It must be air-tight and double glazed to prevent heat loss and leaks. A solar absorber of high efficiency is laid at just above ground level allowing air flow below, above and through the absorber construction to provide efficient heat transfer.

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 solar 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 [1]. This allows daytime solar energy to be stored for electricity generation in the evening and at night.

Theoretical Development

Consider that in Figures 1 - 3

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]

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

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 $\Delta T'$

$$\text{gain in kinetic energy} = \text{mass flow} \;\text{x}\; \text{heat capacity} \;\text{x}\; \text{fall in temperature}$$

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

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.

$$\text{total solar energy absorbed} = \text{mass flow} \;\text{x}\; \text{heat capacity} \;\text{x}\; \text{temperature rise}$$

$$I\, A_3 = \rho\, A_1\, v_1\, C_p\, (\Delta T + \Delta T') \qquad (4)$$

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 1-3, the outer chimney is of diameter 1000 m and height 200 m, that the distance between the concentric chimney walls is 20 m giving an inner chimney diameter 960 m.

$$A_1 = \pi\,(500)^2 - \pi\,(480)^2$$

$$= 19{,}600\,\pi$$

$$= 61{,}544 \text{ m}^2$$

Consider that the inner wall of the solar collector is of diameter 600 m, circumference 1884 m and that there are 60 turbines each of diameter 10 m sited symmetrically around the circumference, one every 31.4 m.

$$A_2 = 60\,(3.14)\,(5)^2$$

$$= 4{,}710 \text{ m}^2$$

The solar collector extends from diameter 600 m to diameter 960 m. It is suggested that the roof of the collector slopes gently from 30 m at the inner circle to 50 m as air flows into the chimney.

$$A_3 = \pi (480)^2 - \pi (300)^2$$

$$= 140{,}400\, \pi$$

$$= 440{,}856 \text{ m}^2$$

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

h	=	200	m	T	=	300	°K
A_1	=	61,544	m^2	g	=	9.81	ms^{-2}
A_2	=	4,710	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	440,856	m^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
				I	=	750	$w\ m^{-2}$

From equation (1)

$$v_1^{\ 2} = \frac{2\ \Delta T}{300} \times 9.81 \times 200$$

$$v_1^{\ 2} = 13.08\ \Delta T \qquad (1)$$

From equation (2)

$$61{,}544\ v_1 = 4{,}710\ v_2$$

$$v_2 = 13.07\ v_1 \qquad (2)$$

From equation (3)

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

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

From equation (4)

$$750 \times 440{,}856 = 1.18 \times 61{,}544 \times 1005\ v_1 (\Delta T + \Delta T')$$

$$v_1 (\Delta T + \Delta T') = 4.530$$

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

$$v_1 \left(\frac{v_1^{\ 2}}{13.08} + \frac{170.7}{2010}\ v_1^{\ 2} \right) = 4.530$$

$$v_1^{\ 3}\ (2010 + 2233) = 4.530 \times 13.08 \times 2010$$

$$v_1^{\ 3} = 28.07$$

$$v_1 = 3.039\ \text{ms}^{-1}$$

$$v_2 = 39.71\ \text{ms}^{-1}$$

$$\Delta T = 0.7061$$

$$\Delta T' = 0.7846$$

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 39.71 ms^{-1} at insolation 750 wm^{-2}. These are eminently reasonable values that could be harnessed by conventional wind turbines.

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

$$= 750 \times 440{,}856$$

$$= 330.6 \text{ MW}$$

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

$$= 0.59 \ (4710) \ (39.71)^{3}$$

$$= 174.0 \text{ MW}$$

Thus the maximum output is 174.0 MW at insolation 750 wm^{-2} representing an efficiency of 52.64%. 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.

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

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

$$= 1.18 \times 61{,}544 \times 3.039 \times 1005 \times 0.7061$$

$$= 156.6 \text{ MW}$$

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.

A sketch of the model proposed is shown in Figure 4

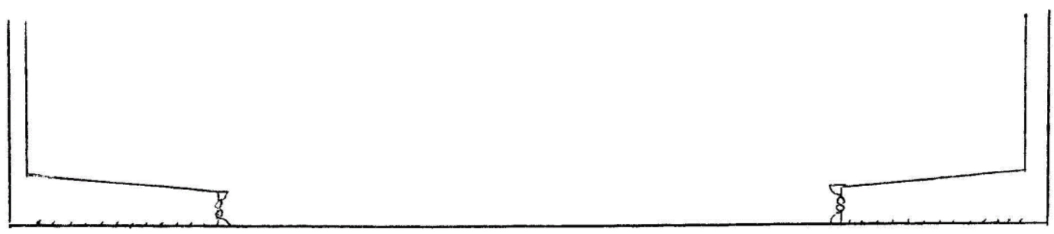

Figure 4 model configuration (to scale)

Slenderness Ratio

Guo et al. [5] draw attention to the importance of the chimney slenderness ratio (SR) which is the ratio of the chimney height to its diameter to maintain good flow in a solar chimney. They suggest an optimum SR of 6 – 8. In the above model the slenderness ratio is

$$\frac{200\ -\ 50}{20} \quad = \quad 7.5$$

Advantages of Annular Chimney

The author suggests adoption of an annular chimney to provide a much larger area of cross-section to multiply volume flow and allow higher flow velocity in the turbines. In the above model the chimney cross-sectional area is 61,544 m^2. If this was to be achieved with a cylindrical solar chimney it would require a diameter of 280 m!! Apart from difficulty in construction, the slenderness ratio requirement above would imply extraordinary height!

The annular chimney may also be much easier to build with its external wall solid down to ground level. The inner wall at a distance of 20 m is amenable to considerable or complete support from the outer wall.

But its main advantage is that **it provides much larger air flow and an optimum slenderness ratio without exceptional height.**

A formula for good efficiency

Schlaich et al. [1] find that the efficiency of a solar chimney is given by

$$\eta \quad = \quad \frac{gh}{C_p\,T}$$

Thus to achieve 100% efficiency with a cylindrical solar chimney requires a height of

$$\frac{1005\ \mathrm{x}\ 300}{9.81} \quad \sim \quad 30{,}000\ \mathrm{m}$$

This is in line with the prediction that a 1000 m height cylindrical solar chimney will have a maximum efficiency of about 3% [1].

The present author [6] argues that when there is venturi multiplication between the cross-sectional area of the chimney (A_1) and the turbines (A_2) velocity through the turbines is multiplied by A_1/A_2 and efficiency by $(A_1/A_2)^2$.

Thus to achieve high efficiency with the present model requires

$$h\left(\frac{A_1}{A_2}\right)^2 \quad \sim \quad 30{,}000$$

In the model described earlier

$$200\left(\frac{61{,}544}{4{,}710}\right)^2 \quad = \quad 34{,}150$$

The efficiency found was 52.64%. The author has taken into account the above formula as a guideline in devising h, A_1, A_2 values for the models that follow in this paper.

Model for a Large Solar Power Station

Consider a configuration with

chimney height	200 m
diameter outer chimney	2000 m
diameter inner chimney	1970 m
diameter inner collector	1200 m

Consider that the inner collector perimeter houses 120 turbines of diameter 10 m; since there is a circumference of 3768 m this means one turbine every 31.4 m. Each turbine is sited at the throat of a convergent nozzle. It is suggested that the diameter of the mouth of the nozzle be 3 times that of the turbine i.e. 30 m. The collector roof is of height 30 m at the periphery rising to 50 m as air enters the chimney. The walls of the chimney are 15 m apart giving a slenderness ratio of

$$\frac{200 - 50}{15} = 10$$

For the configuration described

$$A_1 = \pi\,(1000)^2 - \pi\,(985)^2$$

$$= 29{,}775\,\pi$$

$$= 93{,}493.5 \text{ m}^2$$

$$A_2 = 120\,(3.14)\,(5)^2$$

$$= 9{,}420 \text{ m}^2$$

$$A_3 = \pi\,(985)^2 - \pi\,(600)^2$$

$$= 610{,}225\,\pi$$

$$= 1.916 \text{ km}^2$$

h	=	200	m	T	=	300	°K
A_1	=	93,493.5	m^2	g	=	9.81	ms^{-2}
A_2	=	9,420	m^2	ρ	=	1.18	kg m^{-3}
A_3	=	1.916	km^2	C_p	=	1005	$\text{j kg}^{-1}\text{ K}^{-1}$
				I	=	750	w m^{-2}

Note that in the above configuration $A_1/A_2 = 9.925$. This means that the velocity of the air flow through the turbines is 9.925 times its velocity through the chimney. Thus the available kinetic energy is multiplied by $(9.925)^2 = 98.51$ times that which would be available from the chimney airflow.

Note also that

$$h\left(\frac{A_1}{A_2}\right)^2 = 19{,}700$$

for this configuration predicting a considerably lower efficiency then for the earlier model.

From equation (1)

$$v_1^{\,2} = 2\,\frac{\Delta T}{T}\,gh$$

$$= 2\,\frac{\Delta T}{300}\ x\ 9.81\ x\ 200$$

$$v_1^{\,2} = 13.08\,\Delta T \qquad (1)$$

From equation (2)

$$A_1\,v_1 = A_2\,v_2$$

$$93{,}493.5\,v_1 = 9{,}420\,v_2$$

$$v_2 = 9.925\,v_1 \qquad (2)$$

From equation (3)

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

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

From equation (4)

$$I\,A_3 = \rho\,A_1\,v_1\,C_p\,(\Delta T + \Delta T')$$

$$750\ x\ 1.916\ x\ 10^6 = 1.18\ x\ 93{,}493.5\ x\ 1005\,v_1\,(\Delta T + \Delta T')$$

$$v_1\,(\Delta T + \Delta T') = 12.96$$

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

$$v_1\left(\frac{v_1^{\,2}}{13.08} + \frac{98.51}{2010}\ v_1^{\,2}\right) = 12.96$$

$$v_1^{\,3}\ (2010\ +\ 1288) = 12.96\ x\ 13.08\ x\ 2010$$

$$v_1^{\,3} = 103.3$$

$$v_1 = 4.692\ \mathrm{ms^{-1}}$$

$$v_2 = 46.57\ \mathrm{ms^{-1}}$$

$$\Delta T = 1.683$$

$$\Delta T' = 1.079$$

Maximum insolation $I A_3$ = $750 \times 1.916 \times 10^6$

= 1437 MW

Maximum kinetic energy = $\frac{1}{2} \rho A_2 v_2^{\,3}$

= $0.59 (9420) (46.57)^{3}$

= 561.4 MW

This represents an efficiency of 39.06%.

Large, Efficient Solar Power Stations

The models described in detail above could be early prototypes in a stepwise programme to build increasingly larger solar power stations. Results are summarised in Table 1 for larger configurations of 3 – 5 km diameter. They are presented in the order of steadily increasing output:

174.0 → 561.4 → 1391 → 1740 → 4452 → 8223 MW

The examples on the left are offered as serious possibilities of solar power stations with an efficiency of about 50% that have a maximum output of up to and over 1000 MW. The latter two are included as speculative theoretical possibilities.

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 only about 1°C above ambient minimizing heat loss. 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.

- Dust problems are minimized as incoming air for the turbines and solar collector is drawn from a height of over 200 m around the configuration.

- Solar chimney technology is designed for dry, warm climates. If there is light rain it will wash the collector roof and can be collected as a valuable resource. If there is moderate rain there must be efficient drainage of the runoff from the collector roof.

- The central area of the configuration has available land for development of buildings, housing … Access would have to be by underground tunnel or by losing a small sector of the circular configuration.

- The principles involved in the above configuration - use of natural convection to generate electricity from incoming air and venturi multiplication of air flow velocity using the ratio of area of chimney to turbines - could find application in fossil fuel combustion. It should be possible to generate electricity from natural gas with 70 – 80 – 90% efficiency.

chimney height	200	200	300	300	300	300 m
diameter outer chimney	1000	2000	3000	5000	5000	5000 m
diameter inner chimney	960	1970	2950	4940	4940	4940 m
diameter inner collector	600	1200	2000	4000	3000	2000 m
turbine diameter	10	10	15	20	20	20 m
number of turbines	60	120	130	200	150	100
collector height	30-50	30-50	45-75	60-90	60-90	60-90 m
separation chimney walls	20	15	25	30	30	30 m
slenderness ratio	7.5	10	9	7	7	7
A_1 m^2	61,544	93,494	233,500	468,200	468,200	468,200
A_2 m^2	4,710	9,420	22,960	62,800	47,100	31,400
A_1/A_2	13.07	9.925	10.17	7.455	9.940	14.91
$h\,(A_1/A_2)^2$	34,150	19,700	31,030	16,670	29,640	66,690
A_3 km^2	0.4409	1.916	3.691	6.597	12.09	16.02
v_1 ms^{-1}	3.039	4.692	4.604	4.840	5.464	5.116
v_2 ms^{-1}	39.71	46.57	46.83	36.08	54.31	76.28
ΔT °K	0.7061	1.683	1.080	1.194	1.522	1.334
$\Delta T'$ °K	0.7846	1.079	1.091	0.6476	1.468	2.895
maximum output MW	174.0	561.4	1391	1740	4452	8223
efficiency %	52.64	39.06	50.24	35.17	49.09	68.45

Table 1 Dimensions and Results for Large Efficient Solar Power Stations

Conclusion

A new configuration is proposed for the solar chimney using an annular chimney (ring-shaped) to provide a much larger area of air flow and with turbines sited on the circumference of the solar collector using incoming air. Dimensions are devised to give a high ratio of area of chimney air flow to turbine air flow, thus multiplying the velocity of turbine air flow.

A model configuration is described of chimney height 200 m and diameter 1000 and 960 m. The inner solar collector has diameter 600 m and houses 60 turbines of diameter 10 m sited symmetrically around the circumference. Calculation gives air flow velocity through the turbines of 39.71 ms^{-1} at insolation 750 wm^{-2} giving total available kinetic energy of 174.0 MW with an efficiency of 52.64%. Larger models are also described with maximum output over 1000 MW at an efficiency of about 50%.

The author asks experts on the solar chimney, solar energy or natural convection to evaluate the proposal and to initiate further work on its development.

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