Multichannel solar chimney with multiturbine solar collector

Abstract

The proposal for a multichannel solar chimney, where the chimney is subdivided into a multiplicity of equivalent vertical flow channels, could allow optimal slenderness ratio for a chimney of very modest height. The proposal for a multiturbine solar collector, where parallel rows of turbines are distributed symmetrically throughout a rectangular solar collector, may achieve very high efficiency. These two unproven proposals are brought together in a hybrid configuration. Calculations suggest that a very modest height solar chimney can nevertheless achieve very high efficiency. A variety of sizes of models are considered and suggestions made for further work.

Introduction

The present author has published over 30 papers on his website since 2000 mainly on the solar chimney and often involving some quite radical configurations. The proposal for a multichannel solar chimney is elaborated in two recent papers [1, 2].

One of the parameters in the design of a solar chimney is the slenderness ratio which is the ratio of the chimney height to its diameter. Several research workers have considered the importance of the slenderness ratio; their work has been reviewed by Guo et al. [3] who conclude that there is an optimum value of 6 – 8. This means that a solar chimney of large cross-sectional area must have a very considerable height, typically 500 – 1000m. This presents a major barrier to construction and development of the solar chimney. The present author suggests that if the chimney was sub divided by light, vertical partitions this could create a multiplicity of equivalent, parallel flow channels of optimal slenderness ratio. This could allow a chimney design of large cross-sectional area but of only very modest height.

In another recent paper [4] the present author proposes a rectangular solar chimney with a rectangular solar collector. The latter contains a large number of turbines distributed symmetrically in parallel rows, each row comprising a series of turbines. Calculations show that very high efficiency may be possible with such a configuration.

Both the above proposals are unproven. They need to be examined theoretically and by computer simulation and tested experimentally but the author has moderate confidence that both should work. A hybrid configuration based on the two proposals is developed in this paper.

Theoretical Development

Consider the configuration outlined in Figures 1 - 3

The solar collector has a roof of glass or transparent plastic and an efficient solar absorber at ground level. Consider n rows of turbines each containing n turbines. Each turbine is sited at the throat of a convergent-divergent nozzle.

The chimney is subdivided into a large number of equivalent flow channels using thin polythene partitions. This allows a chimney of relatively very low height to have a good slenderness ratio.

Solar energy is taken up by the absorber warming air in its vicinity which rises into and flows through the chimney. A low wall/barrier and a flap valve prevent back flow. A convection flow is established drawing ambient air into the collector to flow through each successive row of turbines. The air flow is accelerated to high velocity as it flows through the throat of the nozzle. A turbine efficiently extracts this flow kinetic energy. Air flow velocity falls as it flows through the divergent section of the nozzle.

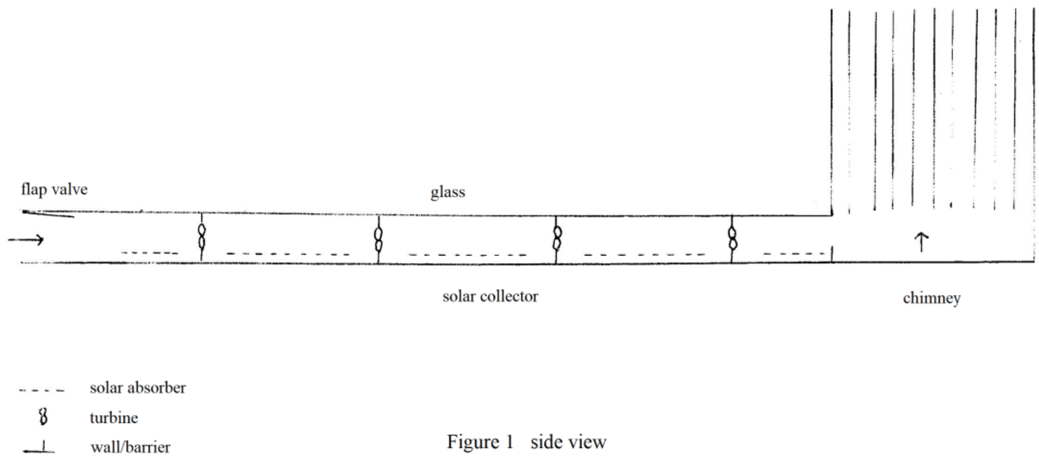

Figure 1 side view

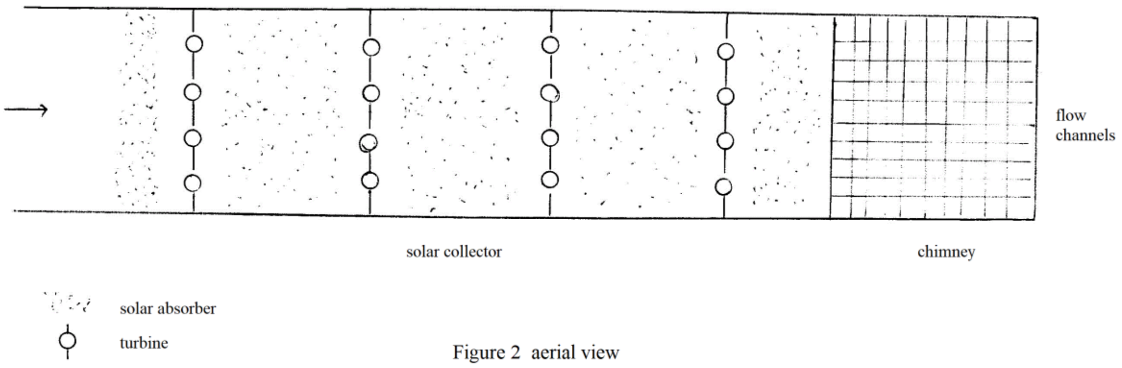

Figure 2 aerial view

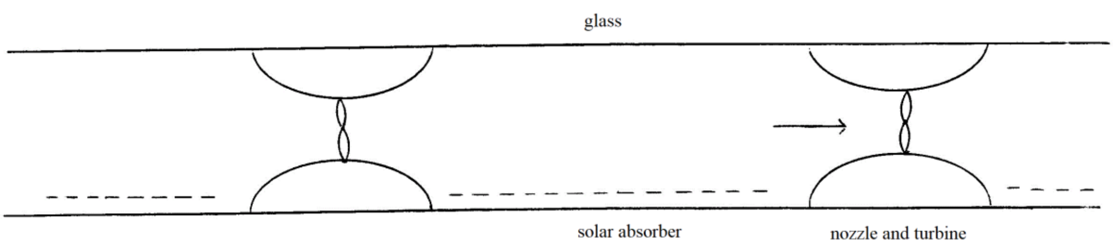

Figure 3 solar absorber/nozzle and turbine repeat units

Consider that in Figures 1 - 3

h	height from solar absorber to top of chimney
A_1	area cross-section of chimney
A_2	area cross-section of each turbine
A_3	area solar absorber
v_1	velocity of air flow through chimney
v_2	velocity of air flow through each turbine
T	ambient temperature
ΔT	excess temperature (above ambient) of exit air
$\Delta T'$	fall in temperature as air flows through each turbine
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 flow in the chimney is given by [5]

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

Constant air flow requires that

air flow in chimney = air flow through each row of turbines

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

As air flows through each nozzle it is accelerated to velocity v_2. The extra flow kinetic energy comes from the internal energy of the air causing 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

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

Solar energy taken up by the absorber provides ΔT for the chimney and $\Delta T'$ for each turbine

total solar energy absorbed = mass flow x heat capacity x temperature rise

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

Equations (1) – (4) define all the energy changes taking place in Figures 1 - 3 and can be used to evaluate different models.

<u>Multichannel solar chimney with multiturbine solar collector and 10 x 10 turbines</u>

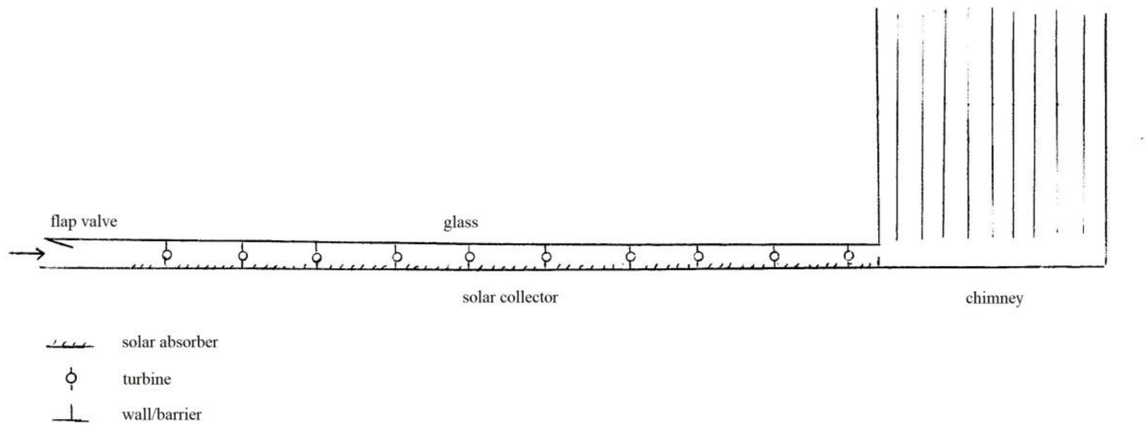

Figure 4 multichannel solar chimney with multiturbine solar collector and 10 x 10 turbines (side view)

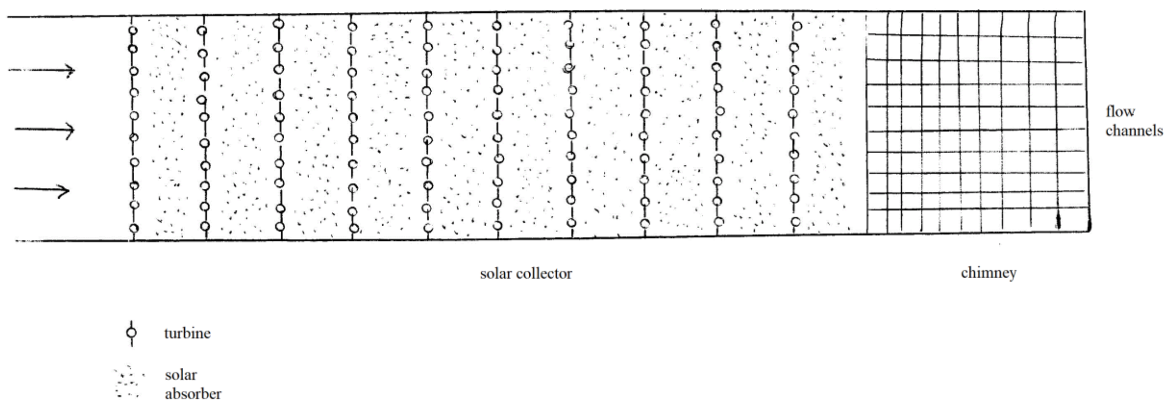

Figure 5 multichannel solar chimney with multiturbine solar collector and 10 x 10 turbines (aerial view)

Consider the configuration shown in Figures 4 and 5.

Consider chimney height 30m and cross-sectional area 30 x 30m. The chimney volume is subdivided into 100 equivalent vertical flow channels of cross-section 3 x 3m giving slenderness ratio 10.

The solar collector has 10 rows of 10 turbines arranged symmetrically. Consider turbine diameter 1m and collector height 3m. The floor of the collector has alternate sections of solar absorber length 6m and nozzle plus turbine length 4m. This gives total solar absorber area
$A_3 = 6 \times 3 \times 10 \times 10 = 1800\ m^2$.

The entire configuration has length 140m, width 30m with chimney overall height 33m.

Equations (1) to (4) apply to the model for which

h	=	30	m	T	=	300	°K
A_1	=	900	m^2	g	=	9.81	ms^{-2}
A_2	=	0.785	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	1800	m^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
n	=	10		I	=	750	$w\ m^{-2}$

The insolation considered represents summer UK maximum.

From equation (1)

$$v_1^{\ 2} = \frac{2\ \Delta T}{300} \times 9.81 \times 30$$

$$v_1^{\ 2} = 1.962\ \Delta T \qquad (1)$$

From equation (2) $\quad 900\ v_1 = 10\ (0.785)\ v_2$

$$v_2 = 114.6\ v_1 \qquad (2)$$

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

From equation (4)

$$750 \times 1800 = 1.18 \times 900 \times 1005\ v_1\ (\Delta T + 10\ \Delta T')$$

Substitute for ΔT from (1) and for ΔT′ from (2) and (3)

$$v_1 \left(\frac{v_1^{\ 2}}{1.962} + 10 \times \frac{13{,}140}{2010}\ v_1^{\ 2} \right) = \frac{1.35 \times 10^6}{1.067 \times 10^6}$$

$$v_1^{\ 3}\ (2010 + 257{,}900) = 1.265 \times 1.962 \times 2010$$

$$v_1^{\ 3} = 0.01919$$

$$v_1 = 0.2677\ ms^{-1}$$

From (2) $\quad v_2 = 30.70\ ms^{-1}$

This gives an air flow through the turbines of 30.70 ms^{-1} at maximum insolation.

From (1) $\quad \Delta T = 0.03654$ °K

From (3) $\quad \Delta T' = 0.4688$ °K

When we consider the configuration as a whole

Maximum insolation $\quad I\ A_3 = 750 \times 1800$

$$= 1.350\ MW$$

For each turbine maximum kinetic energy

$$= \tfrac{1}{2}\ \rho\ A_2\ v_2^{\ 3}$$

$$= \quad 0.59\ (0.785)\ (30.70)^3$$

$$= \quad 13.40 \text{ kw}$$

For 100 turbines maximum kinetic energy

$$= \quad 1.340 \text{ MW}$$

This gives an efficiency of 99.23 %

The efficiency found is extraordinary but in line with the results found in the earlier paper [4]. What is more extraordinary is that this is achieved with a chimney of only 30m height. But this is made possible by the many partitions and 100 flow channels in the chimney allowing a good slenderness ratio with low chimney height.

No experimental work has been conducted on any of the proposals in recent papers but if theoretical calculations were borne out in practice, the above proposal could constitute the 'perfect' solar engine [6].

Proposals for smaller experimental models

The author has developed the above proposal with no experimental work to confirm and no computer simulation to test or validate. Readers are asked to consider such work and ideally to build an experimental model. Aware, however, that contemplating a model containing 10 x 10 turbines may be over-ambitious, the author has set out to devise a series of smaller and more achievable models. These are now presented involving successively 5 x 5, 3 x 3 and 2 x 2 turbines. A summary of the results is then presented in Table 1.

Model with 5 x 5 Turbines

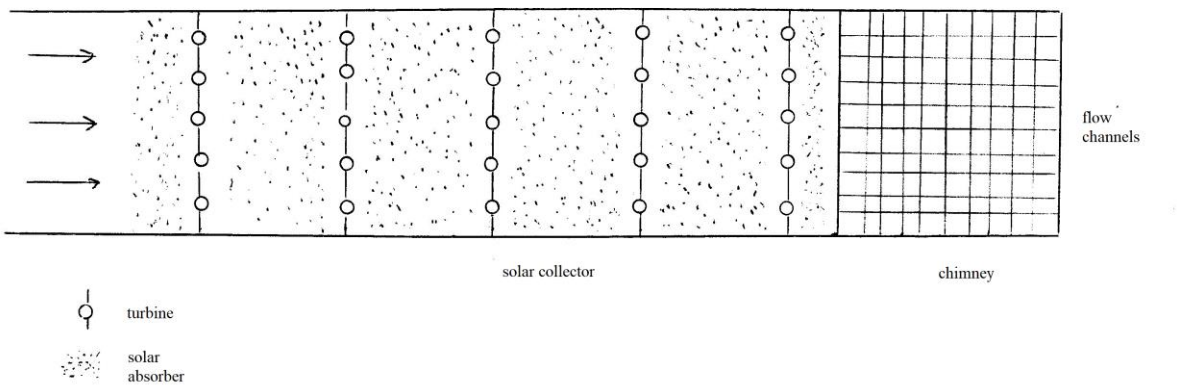

Figure 6 multichannel solar chimney with multiturbine solar collector and 5 x 5 turbines (aerial view)

Consider the configuration outlined in Figure 6

Consider chimney height 15m and cross-sectional area 15 x 15m. The chimney volume is subdivided into 100 equivalent vertical flow channels of cross-section 1.5 x 1.5m giving slenderness ratio 10.

The solar collector has 5 rows of 5 turbines arranged symmetrically. Consider turbine diameter 1m and collector height 3m. The floor of the collector has alternate sections of solar absorber length 6m and nozzle plus turbine length 4m. This gives total solar absorber area
$A_3 = 6 \times 3 \times 5 \times 5 = 450m^2$.

The entire configuration has length 75m, width 15m with chimney overall height 18m.

Equations (1) to (4) apply to the model for which

h	=	15	m	T	=	300	°K
A_1	=	225	m^2	g	=	9.81	ms^{-2}
A_2	=	0.785	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	450	m^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
n	=	5		I	=	750	$w\ m^{-2}$

From (1) $$v_1^{\ 2} = \frac{2\ \Delta T}{300} \times 9.81 \times 15$$

$$v_1^{\ 2} = 0.981\ \Delta T \qquad (1)$$

From (2) $$225\ v_1 = 5\ (0.785)\ v_2$$

$$v_2 = 57.32\ v_1 \qquad (2)$$

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

From (4) $$750 \times 450 = 1.18 \times 225 \times 1005\ v_1\ (\Delta T + 5\ \Delta T')$$

Substitute for ΔT from (1) and for $\Delta T'$ from (2) and (3)

$$v_1 \left(\frac{v_1^{\ 2}}{0.981} + 5 \times \frac{3286}{2010}\ v_1^{\ 2} \right) = \frac{337{,}500}{226{,}800}$$

$$v_1^{\ 3}\ (2010 + 16{,}120) = 1.265 \times 0.981 \times 2010$$

$$v_1^{\ 3} = 0.1376$$

$$v_1 = 0.5162\ ms^{-1}$$

From (2) $$v_2 = 29.59\ \ ms^{-1}$$

From (1) $$\Delta T = 0.2717\ °K$$

From (3) $$\Delta T' = 0.4357\ °K$$

Maximum insolation $$I\ A_3 = 750 \times 450$$

$$= 337.5\ \ kw$$

For each turbine maximum kinetic energy

$$= \tfrac{1}{2}\ \rho\ A_2\ v_2^{\ 3}$$

$$= 0.59\ (0.785)\ (29.59)^{\ 3}$$

$$= 12.00\ \ kw$$

For 25 turbines maximum kinetic energy of 300.0 kw. This gives an efficiency of 88.91%.

Model with 3 x 3 Turbines

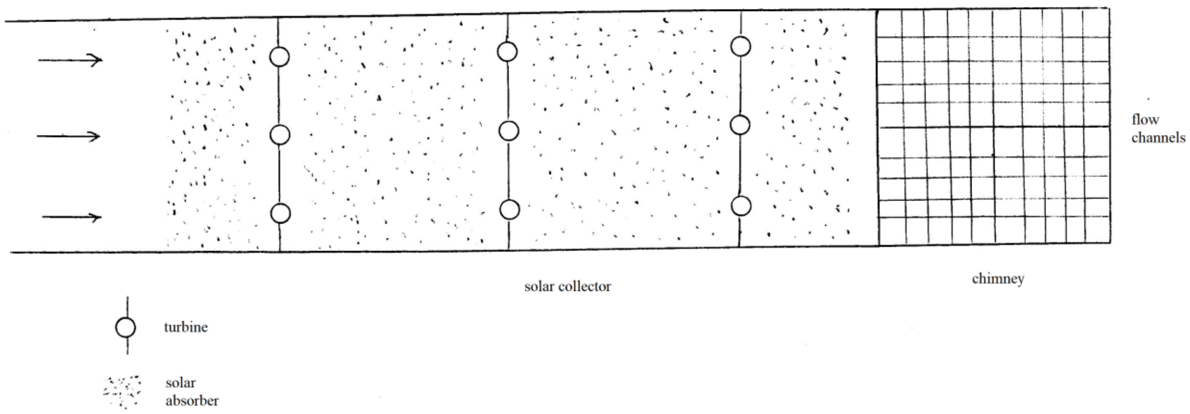

Figure 7 multichannel solar chimney with multiturbine solar collector and 3 x 3 turbines (aerial view)

Consider the configuration outlined in Figure 7

Consider chimney height 10m and cross-sectional area 10 x 10m. The chimney volume is subdivided into 100 equivalent vertical flow channels of cross-section 1 x 1m giving slenderness ratio 10.

The solar collector has 3 rows of 3 turbines arranged symmetrically. Consider turbine diameter 1m and collector height 3m. The floor of the collector has alternate sections of solar absorber length 6m and nozzle plus turbine length 4m. This gives total solar absorber area $A_3 = 6 \times 10 \times 3 = 180\text{m}^2$.

The entire configuration has length 50m, width 10m with chimney overall height 13m.

Equations (1) to (4) apply to the model for which

h	=	10	m	T	=	300	°K
A_1	=	100	m^2	g	=	9.81	ms^{-2}
A_2	=	0.785	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	180	m^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
n	=	3		I	=	750	$w\ m^{-2}$

From (1) $\quad v_1^{\,2} = \dfrac{2\ \Delta T}{300} \times 9.81 \times 10$

$$v_1^{\,2} = 0.654\ \Delta T \qquad (1)$$

From (2) $\quad 100\ v_1 = 3\ (0.785)\ v_2$

$$v_2 = 42.46\ v_1 \qquad (2)$$

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

From (4) $\quad 750 \times 180 = 1.18 \times 100 \times 1005\ v_1\ (\Delta T + 3\ \Delta T')$

Substitute for ΔT from (1) and for $\Delta T'$ from (2) and (3)

$$v_1 \left(\frac{v_1^{\,2}}{0.654} + 3 \times \frac{1803}{2010}\ v_1^{\,2} \right) = \frac{135{,}000}{118{,}600}$$

$$v_1^{\,3}\ (2010 + 3538) = 1.138 \times 0.654 \times 2010$$

	$v_1^{\ 3}$	=	0.2697
	v_1	=	0.6461 ms^{-1}
From (2)	v_2	=	27.44 ms^{-1}
From (1)	ΔT	=	0.6383 °K
From (3)	$\Delta T'$	=	0.3745 °K
Maximum insolation	$I\ A_3$	=	750 x 180
		=	135 kw

For each turbine maximum kinetic energy

$$= \tfrac{1}{2} \rho A_2 v_2^{\ 3}$$

$$= 0.59\ (0.785)\ (27.44)^3$$

$$= 9.565 \text{ kw}$$

For 9 turbines maximum kinetic energy of 86.09 kw. This gives an efficiency of 63.77%.

Model with 2 x 2 Turbines

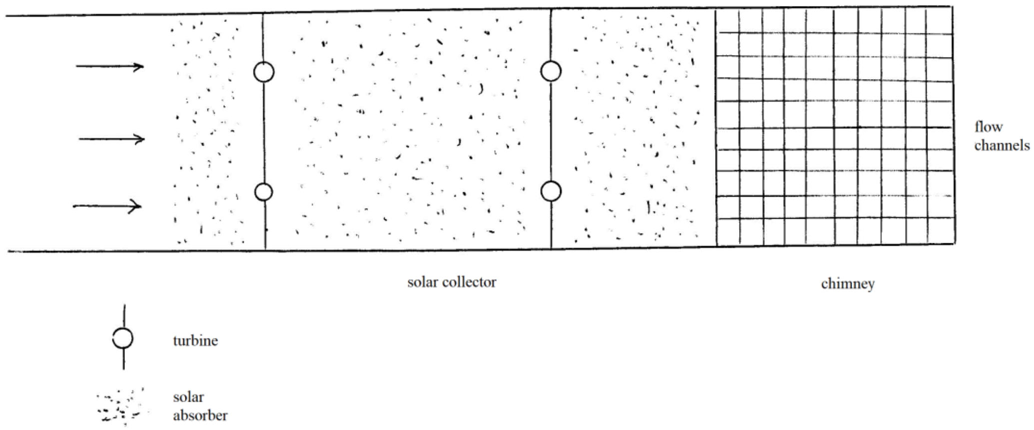

Figure 8 multichannel solar chimney with multiturbine solar collector and 2 x 2 turbines (aerial view)

Consider the configuration outlined in Figure 8

Consider chimney height 5m and cross-sectional area 5 x 5m. The chimney volume is subdivided into 100 equivalent vertical flow channels of cross-section 0.5 x 0.5m giving slenderness ratio 10.

The solar collector has 2 rows of 2 turbines arranged symmetrically. Consider turbine diameter 0.5m and collector height 1.5m. The floor of the collector has alternate sections of solar absorber length 4m and nozzle plus turbine length 2m. This gives total solar absorber area
A_3 = 5 x 4 x 2 = 40m^2.

The entire configuration has length 20m, width 5m with chimney overall height 6.5m.

Equations (1) to (4) apply to the model for which

h	=	5	m	T	=	300	°K
A_1	=	25	m^2	g	=	9.81	ms^{-2}
A_2	=	0.1963	m^2	ρ	=	1.18	$kg\ m^{-3}$
A_3	=	40	m^2	C_p	=	1005	$j\ kg^{-1}\ K^{-1}$
n	=	2		I	=	750	$w\ m^{-2}$

From (1) $\quad v_1^{\,2} = \dfrac{2\ \Delta T}{300} \times 9.81 \times 5$

$$v_1^{\,2} = 0.327\ \Delta T \qquad (1)$$

From (2) $\quad 25\ v_1 = 2\ (0.1963)\ v_2$

$$v_2 = 63.69\ v_1 \qquad (2)$$

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

From (4) $\quad 750 \times 40 = 1.18 \times 25 \times 1005\ v_1\ (\Delta T + 2\ \Delta T')$

Substitute for ΔT from (1) and for $\Delta T'$ from (2) and (3)

$$v_1 \left(\frac{v_1^{\,2}}{0.327} + 2 \times \frac{4056}{2010}\ v_1^{\,2} \right) = \frac{30{,}000}{29{,}650}$$

$$v_1^{\,3}\ (2010 + 2653) = 1.012 \times 0.327 \times 2010$$

$$v_1^{\,3} = 0.1426$$

$$v_1 = 0.5225\ ms^{-1}$$

From (2) $\quad v_2 = 33.28\ \ ms^{-1}$

From (1) $\quad \Delta T = 0.8348$ °K

From (3) $\quad \Delta T' = 0.5510$ °K

Maximum insolation $\quad I\ A_3 = 750 \times 40$

$$= 30\ \ kw$$

For each turbine maximum kinetic energy

$$= \tfrac{1}{2}\ \rho\ A_2\ v_2^{\,3}$$

$$= 0.59\ (0.1963)\ (33.28)^{\,3}$$

$$= 4.267\ \ kw$$

For 4 turbines maximum kinetic energy of 17.07 kw. This gives an efficiency of 56.90%.

Number of turbines	10 x 10	5 x 5	3 x 3	2 x 2	
chimney height h	30	15	10	5	m
chimney cross-section A_1	30 x 30	15 x 15	10 x 10	5 x 5	m^2
flow channels cross section	3 x 3	1.5 x 1.5	1 x 1	0.5 x 0.5	m^2
flow channels number	100	100	100	100	
turbine diameter	1	1	1	0.5	m
area cross-section turbine A_2	0.785	0.785	0.785	0.1963	m^2
collector height	3	3	3	1.5	m
overall height	33	18	13	6.5	m
solar absorber section length	6	6	6	4	m
nozzle plus turbine length	4	4	4	2	m
solar absorber area A_3	1800	450	180	40	m^2
v_1	0.2677	0.5162	0.6461	0.5225	ms^{-1}
v_2	30.70	29.59	29.44	33.28	ms^{-1}
ΔT	0.03654	0.2717	0.6383	0.8348	°K
$\Delta T'$	0.4688	0.4357	0.3745	0.5510	°K
maximum output	1340	300.0	86.09	17.07	kw
efficiency	99.23	88.91	63.77	56.90	%
ground area	140 x 30	75 x 15	50 x 10	20 x 5	m^2

Table 1 Results for multichannel solar chimney with multiturbine solar collector

Discussion

Results for the models suggested in this paper are summarised in Table 1. Parameters have been devised to give values of ΔT and $\Delta T'$ of under 1°C to minimise heat losses from the configuration. They have also been devised to give the maximum velocity of air flow through the turbines, v_2 of about 30 ms^{-1} at maximum insolation. Thus present day wind turbines would be suitable. It should also be noted that air flow velocity will rise and fall very gently during the day in response to variations in insolation minimising stress and wear in the turbines.

The amount of energy produced varies from a maximum 17 kw for the 2 x 2 turbine model to 1340 kw for the 10 x 10 turbine model. These should be economic and could meet the electrical demand of a small cluster of houses for the former to a village or housing estate with hundreds of residential dwellings for the latter.

The proposals made in this paper and the calculations above are based on ideas from earlier papers that have not been tested or validated. They are made in good faith however as ideas that should work. The author asks experts on the solar chimney or more generally on convection or solar energy to carry out theoretical assessments, CFD calculations …. and ideally to build and test one of the smaller models described. If successful results are achieved, then to progress to the larger models which could prove to be highly economic.

Further Comments

- No allowance has been made for energy losses in the solar collector or turbines ... The values of ΔT and $\Delta T'$ are relatively very low so minimising heat losses from the solar collector. Also energy losses in the turbines and generators will be manifested as heat and will be retained in the air flow. They will contribute to buoyancy in the chimney and are effectively recycled.

- Energy storage could be added to the configuration using water bottles placed under the solar absorber [5]. They will absorb heat during daytime air flow which is then released for evening and night generation.

Conclusion

Two unproven proposals are combined in a hybrid configuration for a multichannel solar chimney with a multiturbine solar collector. Calculations show that for a model with 2 rows of 2 turbines with chimney height 5m and ground area 20 x 5m, maximum output is 17 kw with an efficiency of over 50%. Other models considered involve 3 x 3, 5 x 5 and 10 x 10 turbines. For the latter the model has chimney height 30m, ground area 140 x 30m, maximum output 1340 kw and over 90% efficiency. The author asks readers to examine critically the theoretical background and calculations presented … and to build and test one of the smaller models. The configurations described could prove highly economic.

References

[1] www.globalwarmingsolutions.co.uk Multichannel Solar Chimney – dimensions for a demonstration model. July 2020.

[2] www.globalwarmingsolutions.co.uk The Multichannel Solar Chimney – commercial scale. October 2020.

[3] P. Guo, T. Li, B. Xu, X. Xu and J. Li. Questions and current understanding about solar chimney power plant : A review. Energy Conversion and Management 2019, 182, 21-33.

[4] www.globalwarmingsolutions.co.uk Proposal for a rectangular solar chimney with multiple turbines in uniform distribution throughout the solar collector. June 2021.

[5] Schlaich, J., Bergermann, R., Schiel, W. and Weinrebe, G. Design of Commercial Solar Updraft Power Systems – Utilization of Solar Induced Convective Flows for Power Generation. J. Sol. Energy Eng. 2005, 127, 117-124.

[6] Crosbie - Smith, The Science of Energy, The Athlone Press, London, 1998. p 163, Figure 8.3 Rankine's diagram of energy' for the 'perfect' air engine.

Dr Alan Williams *April 2022*